The Transmittal Letter and Report from the Sub-Panel to FESAC Concerning Inertial Confinement Fusion

July 17, 1996

Professor Robert W. Conn
Dean
School of Engineering
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0403

Dear Professor Conn:

In May, you sent me by fax a copy of the charge to the Fusion Energy Sciences Advisory Committee (FEAC) from Martha Krebs, regarding the Inertial Fusion Energy (IFE) program of the Office of Fusion Energy Sciences. Enclosed is a copy of the Charge.

The panel of technical experts (see Enclosure 2) that I chaired held two meetings in June, one at the Lawrence Berkeley National Laboratory and one at the Lawrence Livermore National Laboratory. We received input from DOE/OFES and DOE/DP/ICF and from numerous experts from the many institutions involved in inertial fusion research.

The new mission of the OFES is to "Advance plasma science, and fusion technology-- the knowledge base necessary for an economically and environmentally attractive energy source for the nation and the world".

Because of the short time given to respond to this charge, we decided to rely on background information contained in the FEAC-7 report of a more extensive review of this subject published in 1993, and to hear mainly about programs since that time.

Our panel has the following findings:

(1) Progress in the IFE program since the 1993 FEAC-7 review has been good, despite its being funded at the $8 million per year level, rather than the then-recommended $17 million level.

(2) A strong IFE program is a proper and important component of the restructured OFES/DOE program. Challenging and relevant scientific issues need to be resolved, notably in collective effects in high current accelerators and beam-plasma interactions.

(3) With DP/ICF physics development and supporting science and technology and the high repetition rate driver development in the OFES/IFE program, the United States is positioned to lead the world in IFE science and technology.

(4) There has been significant progress since 1993; a substantial declassification in the DP/ICF area allows wider participation and more rapid scientific progress; in progress in preparation for the National Ignition Facility (NIF); in target physics; heavy ion accelerator technology; in operation of improved laser systems; operation of light-ion systems; and in improved understanding of power plant issues.

(5) The inertial fusion program involves much exciting science and technology, and there are opportunities because of declassification to broaden the work in the IFE program. The work of LBNL, LLNL and the institutions is of high scientific gravity.

(6) There are numerous challenges in physics and technology but there are no show-stoppers.

(7) The time frame is set by a succession of anticipated events in the DP and the OFES programs. In the restructured OFES program, it is envisaged that there will be "a growing portfolio of new experiments". By 1999, the International Thermonuclear Experimental Reactor Engineering Design Activities will be complete, if the presently proposed schedule is followed the NIF should be well advanced in its construction phase , and the Tokamak Fusion Test Reactor program at the Princeton Plasma Physics Laboratory will be completed. This is a period in which some new initiatives--including one in IFE--should be ready for consideration by OFES. The NIF program is designed to have the capability to ignite a D-T target in the 2005 time frame.

(8) The heavy ion driver is the most promising for energy applications because of its greater efficiency, about 3 times greater than laser driver candidates. Further, the induction linac approach is the most likely to meet performance/cost targets.

In the longer term, breakthroughs in the development of laser systems could change these conclusions, and reassessments should be made on a regular basis.

(9) There is a need for an Integrated Research Experiment (IRE) to have in one facility the ability to resolve basic beam dynamics, final beam focusing and transport issues in a reactor relevant beam parameter regime, and to evaluate the target heating phenomonology. Progress in beam development encourages the belief that the conceptual design of a 3kJ-30kJ, ~100 MeV driver could be developed around 1999, provided there is continued support for accelerator development.

(10) Target physics will not be tested conclusively before the experiment on NIF. LLNL has just completed an integrated simulation of a heavy ion driver target. It is important for other groups to develop new codes and to perform independent confirmatory simulations. Such efforts, would provide an important link between the MFE and the IFE communities.

(11) Several comprehensive conceptual design and system studies have been completed. They show the potential for and the requirements for IFE to provide competitive power plants. The IFE program within OFES should have sufficient breadth beyond driver development to cover those other areas that are critical to its feasibility and competitiveness.

As a first priority, we suggest work on wall protection scheme evaluations and development and confirmatory simulations of heavy ion driver performance. As a second priority, there should be work on cavity clearing technologies at IFE repetition rates and the development of final focusing optics for lasers (we assume that focusing and transport work for beams will be undertaken as a part of the accelerator development program.) As a third priority, work on target factory studies, rep-rated laser systems (a promising area but the present funding level will only support development of the most promising driver), shielding, blanket and tritium studies, and further detailed power plant conceptual design studies.

(12) We suggest that a joint IFE steering committee, between ER and DP, consisting of all interested parties, should review the program on a regular basis, and define the expectations for the ER and DP parts of the program. In addition, this steering committee could facilitate international collaboration.

(13) The position of the Panel is that there should be an increase in the non-driver part of the IFE program, raising it from the present ~\$1M per year to \$2-3M per year. It is noted that if this were done at a constant level of about \$8M per year it would substantially slow the pace of accelerator development. In fact, the FEAC-7 report identifies the \$5M per year case as one in which there is no credible program for the development of a heavy ion fusion energy option. The following finding, concerning funding for the IFE program, represents a medial opinion of the Panel. A minority of the Panel would support a more aggressive approach and a comparable minority, a less aggressive approach.

The medial opinion is that funding for the IFE program should be increased to about $10M per year for the next few years to strengthen the scientific and technological understanding of the prospects of IFE and to involve a wide range of institutions in these efforts. Such an annual budget would allow maintaining the pace of heavy ion accelerator development. In total, the program would provide the breadth of support necessary for initiation around the year 2000 of a construction project for an integrated research experiment using a multi-kJ heavy ion driver with a target chamber. An increased budget in the 1999 time frame would be required for developing such a proposal.

Sincerely,

/S/

John Sheffield
Chair, on behalf of the FEAC/IFE panel

Enclosures

Charge from Martha Krebs, Director of DOE Energy Research

"Charge to Fusion Energy Advisory Committee for an Inertial Fusion Energy Review

Since 1990, the fusion program has had a mandate to pursue two independent approaches to fusion energy development, magnetic and inertial confinement fusion. In magnetic fusion, our strategy is to continue to use international collaboration, especially participation in the International Thermonuclear Reactor to pursue fusion energy science and technology. In inertial fusion, our strategy has been to assume the target physics is the highest priority activity and would be developed as a part of weapons research program; and, indeed, the next step in the development of target physics, namely the National Ignition Facility, is proceeding into construction in Defense programs.

Based on the Fusion Policy Advisory Committee Report of 1990, we had taken as our highest priority in inertial fusion energy the development of heavy ion accelerators as the most desirable driver for energy applications. That development program has met all of its milestones and has received numerous positive reviews, including one by the Fusion Energy Advisory Committee (FEAC), which in 1993 recommended a balanced Inertial Fusion Energy program of heavy ion accelerator development, plus other smaller scale efforts, at $17 million per year.

The potential for inertial fusion energy has been judged to be real, but the fusion program no longer has as a goal the operations of a demonstration power plant by 2025. Given that the basic mission of the fusion program has changed from energy development to fusion science, and that funding for the entire fusion program will be constrained for some number of years, I would like FEAC to again consider inertial fusion energy and recommend what the new Fusion Energy Sciences program should be doing in support of this future fusion application, and at what level."

FESAC/IFE REVIEW

PANEL MEMBERS

Mohamed Abdou	University of California Los Angeles
Richard Briggs	Science Applications International Co.
James Callen	University of Wisconsin
*John Clarke	Pacific Northwest National Laboratory
*Harold Forsen	Bechtel (retired)
*Katharine Gebbie	National Institute of Science and Technology
Ingo Hoffman	Gesellschaft fuer Schwerionenforschung Darmstadt, Germany
John Lindl	Lawrence Livermore National Laboratory
*Marshall Rosenbluth	University of California, San Diego
John Sheffield (chair)	Oak Ridge National Laboratory
William Tang/ Ernest Valeo	Princeton Plasma Physics Laboratory

*Members of FESAC

REPORT OF THE FESAC/IFE REVIEW PANEL

July 19 1996.

Panel members.

Mohamed Abdou	University of California Los Angeles.
Richard Briggs	Science Applications International Co.
James Callen	University of Wisconsin.
*John Clarke	Pacific Northwest National Laboratory.
*Harold Forsen	Bechtel (retired).
*Katharine Gebbie	National Institutes of Science and Technology.
Ingo Hoffman	Gesellschaft fuer Schwerionenforschung, Darmstadt, Germany.
John Lindl	Lawrence Livermore National Laboratory.
Earl Marmar	Massachusetts Institute of Technology
William Nevins	Lawrence Livermore National Laboratory.
*Marshall Rosenbluth	University of California, San Diego.
John Sheffield (chair)	Oak Ridge National Laboratory.
William Tang/ Ernest Valeo	Princeton Plasma Physics laboratory

* Members of FESAC.

TABLE OF CONTENTS

A. CHARGE TO PANEL

This report provides an analysis by a Fusion Energy Advisory Committee (FEAC) Panel, of future program options for the Inertial Fusion Energy (IFE component of the Fusion Energy Sciences Program of the Office of Fusion Energy Sciences. The report is in response to the following request to FEAC from the Director of the Office of Energy Research:

> "Charge to the Fusion Energy Advisory Committee for an Inertial Fusion Energy Review.

Since 1990, the fusion program has had a mandate to pursue two independent approaches to fusion energy development, magnetic and inertial confinement fusion. In magnetic fusion, our strategy is to continue to use international collaboration, especially participation in the International Thermonuclear Reactor, to pursue fusion energy science and target technology. In inertial fusion, our strategy has been to assume the target physics is the highest priority activity and would be developed as a part the weapons research program; and, indeed, the next step in the development of target physics, namely the National Ignition Facility, is proceeding into construction in Defense programs.

Based on the Fusion Policy Advisory Committee Report of 1990, we had taken as our highest priority in inertial fusion energy the development of heavy ion accelerators as the most desirable driver for energy applications. That development program has met all of its milestones and has received numerous positive reviews, including one by the Fusion Energy Advisory Committee (FEAC), which in 1993 recommended a balanced Inertial Fusion Energy program of heavy ion accelerator development, plus other smaller scale efforts, at $17 million per year.

The potential for inertial fusion energy has been judged to be the fusion program no longer has as a goal the operation of a demonstration power plant by 2025. Given that the basic mission of the fusion pro has changed from energy development to fusion science, and that funding for the entire fusion program will be constrained for some number of years, I would like FEAC to again consider inertial fusion energy and recommendation what the new Fusion Energy Sciences program should be doing in support this future fusion application, and at what level."

B. REVIEW PROCESS

The panel was briefed by Dr. N. Anne Davies, Director of the Office of Fusion Energy Sciences (OFES) of the Office of Energy Research, and by Dr. David Crandall, Director of the Office of Inertial Confinement Fusion (lCF) and the National Ignition Facility (NIF) of Defense Programs, on the roles of IFE and 1CF in the Department of Energy. A summary was given of previous reviews of the IFE program, including that of the Fusion Policy Advisory Committee (1990) and the FEAC Panel 7 (1993). The panel was asked by Dr. Davies, and agreed to assume, that NIF would be built and that the IFE mission belonged in OFES. Presentations were also heard on the progress and prospects in the various areas of the program from a number of the collaborating institutions. Written comments were received from experts in the field. The agendas of the meetings and a list of contributors are provided in Appendix A.

It was agreed that, given the short timescale for conducting this review, the panel would rely on the extensive technical background provided in the FEAC Panel 7 report, supplemented by the more recent information given in presentations and written comments. Updates to some of the appendices of the Panel 7 report are appended -- Target Physics for IFE (Appendix B), and IFE Power Plant Issues and Needed Breadth of Research (Appendix Q.

C. OVERVIEW

Inertial confinement of plasmas provides an important fusion option with the potential for a competitive power plant. There are two inertial fusion program elements. The OFES/OERIDOE has the mandate to support energy applications through its Inertial Fusion Energy (IFE) program. The ICF program in DP/DOE is motivated by science based stockpile stewardship. The DP program is funded in FY 1996 at about $240 M/year, about 30 times the OFES inertial fusion energy program. Obviously, much of the key research will be undertaken in the DP program. The IFE program must concentrate on energy issues not covered by DP, and try to position itself to apply the results of DP research in the energy area. Significant developments in the ICF program continue to provide crucial scientific and technical results that support the

EFE component. It is important to capitalize on this symbiotic relationship between EFE and ICF. Further, progress in the EFE program since the 1993 FEAC-7 review has been good, despite its being funded at the $8M per year level rather than the then-recommended $17 M level.

A strong IFE program is a proper and important component of the restructured OFES/DOE program. Challenging and relevant scientific issues need to be resolved, especially in the areas of collective effects in high current accelerators and beam-plasma interactions. With the ICF physics development in Defense Programs, and supporting science and technology and the high repetition rate driver development in the OFES program, the United States is positioned to lead the world in developing EFE science and technology.

The following finding, concerning funding for the IFE program, represents a medial opinion of the Panel. A minority of the Panel would support a more aggressive approach and a comparable minority, a less aggressive approach. The medial position of the Panel is that there should be an increase in the non-driver part of the EFE program beyond the present level to strengthen the scientific and technological understanding of the prospects of EFE and to involve a wider range of institutions in these efforts. The medial opinion is that, to achieve this goal, the funding for the EFE program should be increased to about $10M per year for the next few years. Such an annual budget would allow maintaining the pace of heavy ion accelerator development. In total, the program would provide the breadth of support necessary for initiation around the year 2000 of a construction project for an integrated research experiment using a multi-kJ heavy ion driver with a target chamber.

D. FINDINGS

1. Progress Since 1993.

- An opportunity for wider participation and more rapid scientific progress has been created by a substantial declassification in the ICF area funded by DOE's Defense Programs;

- The progress in the preparation of the National Ignition Facility (NIF), for which the Inertial Confinement Fusion Advisory Committee (ICFAC, November 1995) indicated that "as far as ignition is concerned there is sufficient confidence that the program is ready to proceed to the next step in the NIF project ...."?

- Excellent progress in:

  - the understanding of target physics through the NOVA program;
  - heavy ion accelerator technology;
  - operation of improved, fusion relevant, laser systems -- KrF (Nike at NRL), the new Omega Upgrade Direct Drive Facility (U. Of Rochester) and diode pumped solid state development (at LLNL);
  - operation of light ion systems that support some beam-target interaction assumptions; and
  - improved understanding of power plant issues and refinements that could lead to competitive fusion power plant prospects.

2. Science and Technology.

The inertial fusion program involves much exciting science and technology, as seen in the continuing developments in the target physics area. Although most of the science of target design and implosion is undertaken in the ICF Program, there are opportunities, because of declassification, for a broadening of the work in the IFE Program. The development of energetic, high current density, space-charge-dominated beams and their focussing onto a target involves fundamental science -instabilities, beam-plasma interactions, plasma lenses, etc. -- and a great opportunity to compare sophisticated computer models with experiments. These developments will have importance broadly across the accelerator field. The development of the drivers and of power plant systems requires innovative new technologies. Work to date has already led to some significant advances.

The panel finds the work at LBNL to be of high scientific quality and was impressed that the ongoing theory and experiments, even at present funding levels, will contribute significantly to the science base required for heavy ion driver development and beam propagation. The complementary IFE programs at LLNL and other institutions have also made impressive progress.

3. Challenges.

Many scientific and technological challenges remain to be overcome before the goal of an economic power plant can be realized. Success is not assured although we see no show stoppers. In rough order of importance, the most critical of these are:

- Overcoming the hydrodynamic instabilities (and possible laserplasma or beam plasma instabilities), and obtaining adequate symmetry to produce a high gain target yield. We must rely on NIF for the basic experimental proof or disproof.

- Providing viable protection of the target chamber against the X-rays, neutrons, blast, and debris to be expected from the pellet explosion. This may be particularly critical for the final focusing optics of a laser system. An analogous issue for heavy ions is finding an adequate mode for beam transport, compatible with the chamber environment that is present with various wall protection schemes.

- Development of a driver with adequate efficiency, rep-rate, and reliability.

- Mass producing targets at a cost of about $0.25 apiece, including their injection and accurate positioning in the target chamber.

All of the above must of course be done at a cost compatible with economic electricity production.

4. Timeframe.

The pace and content of the EFE program is driven by a succession of anticipated events in the DP and OFES programs:

- In the Restructured Fusion Energy Sciences Program, it is envisaged that there will be "a growing portfolio of new experiments . .

- By 1999, the International Thermonuclear Experimental Reactor Engineering Design Activity will have been completed, the NIF should be well advanced in its construction phase, assuming the presently proposed- schedule is met, and the Tokamak Fusion Test Reactor program at PPPL will be completed. This is a period in which some new initiatives - including one in IFE -- should be ready for consideration by OFES.

- The proposed NIF program is designed to have the capability to ignite a D-T target in the 2005 timeframe.

5. Opportunity for the U.S. in IFE.

A strong IFE program is a proper and important component of the restructured OFES/DOE program. Challenging and relevant scientific issues need to be resolved, especially in the areas of collective effects in high current accelerators and beam-plasma interactions. With the ICF physics development in Defense Programs and supporting science and technology and the high repetition rate driver development in the OFES program, the United States is positioned to lead the world in developing IFE science and technology.

6. Logic for Heavy Ion Accelerator Driver.

In agreement with previous reviews of inertial fusion energy by the National Academy of Sciences and two FEAC panels, we consider the heavy ion accelerator to be the most promising driver for energy applications. The reasons include the relatively high efficiencies that are possible with accelerators, exceeding 30%, and the demonstrated high reliability of high power accelerators operating at rep rates of several Hz. In contrast, the best laser options - KrF and DPSS - have efficiencies less than 10%. Among the alternatives for heavy ion accelerators, the induction linac (or possibly the recirculating version) is well matched to the multikiloamp currents and submicrosecond pulse lengths required for inertial fusion.

An alternative accelerator approach is the rf/storage ring driver. This approach fits well within the existing European accelerator programs, and is a valuable complementary program. In a presentation at the review meetings, our European panel member agreed that the induction linac has potential cost advantages in comparison with the rf linac/storage ring approach they are exploring.

In the longer term, breakthroughs in the development of laser targets, including direct drive and other approaches (such as the fast ignitor do - A described below) could modify the decision on drivers. Reassessment of the driver and target should be made on a regular basis.

7. Need for Integrated Research Experiment.

Excellent progress has been made in the past by the IFE Program in accelerator development on key issues (e.g., beam bending, merging, pulse compression, final transport) through a series of small scale experiments - closely coupled with theoretical modeling - to understand fundamental aspects of the basic beam phenomenology. These innovative small scale experiments and associated theoretical modeling should continue. However, progress at the level needed to fully evaluate the HIF approach to IFE will also require an integrated experiment capable of resolving the basic beam dynamics issues in the accelerator, studying the final focusing and transport issues in a reactor-relevant beam parameter regime, and evaluating the target heating phenomenology.

With a succession of delays in the funding of the (less ambitious) ELSE project, the IFE team believes a more comprehensive "Integrated Research Experiment" (IRE) should be the focus of the next decade of IFER research and development. The IRE is discussed in more detail in section IID. The overall objective of IRE is to provide the data base needed to support a decision to proceed with the construction of a full scale IFE driver, on a time scale consistent with NIF demonstrations of fusion target performance.

While various options for such a facility have been considered over the years, no particular option has been selected. Consequently, the Panel received only limited information on this topic. Nevertheless, it seems clear that trade studies of various options leading to the development of a conceptual design for the IRE should be a major focus of the heavy ion program over the next two to three years.

8. Target physics.

The key scientific issue for any IFE system is target physics. This will not be tested conclusively before the experiments on the NIF. Nonetheless, the best possible simulations are indicated for a program of this importance and scientific value. LLNL has just completed the first successful "integrated' simulation of a heavy ion driven target. We believe it is important for other groups to develop new codes and perform independent confirmatory simulations as one element in a driver decision. We believe that the recent declassification makes this feasible, and that this essential task could be undertaken by an MFE theory group, providing an important fink between the MFE and IFE communities with eventual mutual enrichment. Developing new target physics codes is a challenging multiyear project. In the interim, MIZE theorists could contribute to such issues as beam propagation, and participate in target design using existing codes.

9. Program Needs Derived from Power Plant Studies.

Several comprehensive, conceptual design and systems studies have been completed. They show the potential for and requirements for IFE to provide competitive power plants. Other than development of the driver, the key issues are:

- Demonstration of high gain at moderate driver energy.
- Development of chamber technology, including wall protection and cavity clearing schemes at power plant, repetition rates.
- Development of power plant technologies to provide tritium selfsufficiency, radiation shielding, radiation resistant materials, and low-cost target production.

The IFE program within OFES must have sufficient breadth, beyond driver development, to cover those other areas that are critical to its feasibility and competitiveness. Progress in these areas will influence driver research priorities and should provide the data needed in the near term to perform meaningful experiments on NIF that are important to IFE.

10. Priorities Outside Heavy Ion Accelerator Development.

The panel suggests the following priorities for the broader program:

First priority:

- Wall protection scheme evaluations and development.
- Confirmatory simulations of heavy ion driver target performance.

Second priority:

- Cavity clearing technologies at IFE repetition rates.
- Development of the final focussing optics for laser systems. (It is assumed that final focussing and support studies for heavy ion beams are undertaken as a part of the accelerator development program).

Third priority:

- Target factory atudies.

- Work on rep-rated laser systems. This is an important area but until IFE funding increases substantially, development of only the presently most promising driver can be afforded.
- Shielding, blanket and tritium studies.
- Detailed power plant conceptual design studies. The extensive studies made in recent years have identified the principal issues for IFE. It is time now to concentrate the scientific and technological studies on these specific issues.

11. Roles of DOE/Energy Research and DOE/Defense Programs, and international Collaboration.

This Panel has reviewed and commented on the 1FE program conducted by the OFES of Energy Research. The program benefits from an essential symbiotic relationship with the ICF program conducted by Defense Programs. The Panel notes that the NIF program expects to offer testing time to a range of institutions and program interests. A 1994 workshop, organized by DP, identified a wide range of IFE relevant issues that could be addressed by NIF. The Panel is not in a position to comment on the balance between the various elements of the DP program, but feels strongly that greater clarification is needed regarding possible implementation of these IFE relevant elements of the DP-supported ICF program.

A joint IFE steering committee between ER and DP, consisting of all interested parties, should review this program on a regular basis.

In addition, such a committee might be used to facilitate international cooperation in IFE. This FESAC/IFE panel did not review the foreign programs, except for a brief discussion of some European developments (see IIC). We note, however, that the French are building a NIF-scale facility, that there is a proposal in Europe to expand IFE, and that there are significant IFE programs in Japan and Russia.

12. Budgets.

The position of Panel is that there should be an increase in the nondriver part of the IFE program beyond the present level to strengthen the scientific and technological understanding of the prospects of IFE and to involve a wider range of institutions in these efforts. We believe that this is needed even though there is a large measure of breadth because of related DP-funded efforts. For a total OFES/IFE budget in the range of $8M or greater, this total investment in non-driver science and technology should be $2M - $3M per year.

The following finding, concerning funding for the IFE program, represents a medial opinion of the Panel. A minority of the Panel would support a more aggressive approach and a comparable minority, a less aggressive approach. The medial opinion is that funding for the IFE program should be increased to about $10M per year for the next few years to strengthen the scientific and technological understanding of the prospects of IFE and to involve a wide range of institutions in these efforts. Such an annual budget would allow maintaining the pace of heavy ion accelerator development. In total, the program would provide the breadth of support necessary for initiation around the year 2000 of a construction project for an integrated research experiment using a multi-kJ heavy ion driver with a target chamber. An increased budget in the 1999 timeframe would be required for developing such a proposal.

At the present OFES/IFE budget level of $8M, a significantly increased investment in program breadth is desirable but would be achieved at the expense of a substantial slowing of the pace of development of a heavy ion accelerator. At lower budget levels, the elements of the program would have to be done serially rather than in parallel, delaying the pace of the program beyond that needed to meet the goals above. At some lower level, it would be impossible to mount a coherent driver development program. The FEAC Panel report identified the $5M/year case as one in which "there is no credible program for the development of a heavy ion fusion energy option."

II. BACKGROUND INFORMATION

A. Target Physics.

The gain required for an ion-beam power plant can be estimated from the requirement that the recirculating electrical power should be limited to about 25%, and hence 10% of the output fusion thermal power. For an assumed accelerator efficiency of 35%, gains of about 30 are needed.

Recent LLNL integrated calculations of 2-sided, indirectly driven ion target designs predict a gain of 40-50 with a 6-7 MJ driver capable of focussing to a 6 mm radius spot size. These calculations consider the ion energy conversion to X-rays in the target, and the subsequent radiation transport and pellet implosion. Most of the calculation involves the same physics as that involved in the LLNL NIF laser implosion predictions, which have been verified by LANL simulations. The validity of these codes has been tested against Nova experiments and judged (by ICFAC for example), to provide an adequate basis for proceeding with NIF. We conclude by analogy that an adequate basis of target physics exists for proceeding with consideration of other aspects of an HIF design. A wide variety of possible target designs for HIF requires further study. It is very likely that more optimum designs are feasible. We believe that it would be desirable if independent propagation and target physics codes would be implemented and we recommend that the participation by scientists from one or more MFE groups be encouraged.

There are alternative concepts for IFE reactors. Direct drive targets, while requiring very high uniformity, allow better coupling of driver energy to compressed fuel (by a factor of 2-5) and hence potentially higher gain. Such advantages in gain might allow KrF lasers or DPSSL's to overcome the large efficiency advantages of HIF. Experiments on the Omega facility (University of Rochester) and NIKE facility (NRL) should give some quantitative data on these prospects in the next several years. Direct drive HI targets are in principle feasible, but questions regarding deposition nonuniformity from such sources as beam overlap and multiple-beam interactions have not been adequately evaluated.

Still more dramatic improvements in gain or minimum size may be available with the fast ignitor. Many physics and technology issues remain to be explored, and the first significant data base on this exciting new prospect will become available in the next 2-3 years on Nova.

We conclude that indirect-drive HIF remains the driver option of choice. Enough data should be forthcoming on direct drive and fast ignitor prospects in the next 3-4 years, that it should be possible to better evaluate the prospects of IFE with lasers at that time.

B. Heavy Ion Accelerator (Progress, Issues and Prospects).

1.) Progress since 1993 on issues identified by FEAC panel 7 (page 7)

The LBNL injector program has demonstrated the production and acceleration of a single driver-scale ion beam, in a linear geometry. The parameters of the beam are 2MeV, 0.25mC/m (790 mA) of K+, with emittance of Imm-mr. Beam energy variation (< ±0.15%) is also consistent with the full-scale driver requirements. The goal of producing a multibeam injector was not met because funding was not provided. A schematic diagram of an accelerator experiment, indicating issues and progress, is shown in the figure below.

Matching a high-current beam into an alternating gradient (quadrupole) channel is important. Experiments are beginning with a quadrupole matching section; 3-D computer simulations project successful operation.

Transverse beam combining is considered advantageous because it allows for electrostatic quadrupole transport of many beams (at low energy) with small apertures. Once combined (at about 100 MeV), subsequent acceleration and transport is carried out with magnetic quadrupoles that have large apertures. Beam combining experiments have begun at LBNL.

Transport of a low-current space charge dominated beam (mAs) through a 7-quadrupole magnetic focussing system has been achieved successfully at LLNL. Construction has started at LBNL of a high current (800 mA) system.

Recirculation is being investigated; potential advantages include reduced total length, saving on total number of induction modules, and allowing smaller individual induction modules. An overall reduction in cost could thus be realized. Many issues must be dealt with here: beam control is likely to be more difficult; emittance growth in a curving beam with space charge effects needs evaluation; the pulsers must be programmed with a different time history for each pass of the beam; energy recovery from dipoles appears necessary; and vacuum requirements are significantly more stringent (- 2 orders of magnitude). A prototype recirculator is being developed at LLNL to address many of these issues experimentally; it is no expected to have a functioning 360 degree ring before FY98.

Final focusing of the beam onto target presents numerous scientific and technical challenges. Preliminary experiments have begun at LBNL; on self-focusing (plasma lens), have led to a 20-fold increase in beam intensity; and on laser-induced plasma channel guiding; much more work needs to be done in this area in the future.

In parallel with the experimental investigations, theoretical modeling of beam transport and dynamics has made excellent progress in the last few years. Highlights include: particle in cell simulations of beam merging results; detailed modeling of beam transport through electrostatic quadrupoles, with space-charge effects; simulations of the recirculator approach, which are used to help design the experiments; evaluation of resistive wall mode effects on longitudinal beam stability; numerical studies of chamber focusing and transport, including effects of charge and beam neutralization; investigation of beam-beam interactions for multiple beams converging near the target.

There has been a number of hardware developments. Lower cost ferromagnetic materials have resulted from making better use of industrial products. High repetition rate, reliable, flexible waveform controllers and generators have been developed for beam acceleration. Low-cost pulsed magnetic quadrupoles and a high gradient (100 kV/m) electrostatic quadrupole system has been developed.

The studies described above were carried out primarily to support the design and experimental program of the Induction Linac Systems Experiments (ILSE) accelerator. The advances described above would allow an ILSE-type accelerator to have twice the performance at a similar cost to the original proposal. This experience leads to the expectation that much larger gains in performance will be achieved in the proposed program over the next few years. For these reasons the program is considering an integrated experiment with a 3-3OkJ accelerator as the next step.

2.) Issues in the near term program.

- Continued development of ion sources to achieve longer life and lower emittance is needed.
- Development should continue on compact multi-beam, high current injectors.
- A demonstration is required of the injection and multi-pass recirculation of a space charge dominated beam, while maintaining beam quality.
- The maximum transportable current density limits should be determined.
- Validation of beam simulation codes for 100's of lattice periods is required.
- Demonstrations of beam combining are required with validation of codes, and of beam focussing with and without neutralization.
- Development is also required of low cost components and assembly

techniques.

3.) Feasibility of Heavy-Ion-Beam-Drive for High-Gain Targets:

It must be demonstrated that high-gain targets can be driven by heavy ion beams. Some modeling has been carried out to investigate this very broad issue, and there is some related information from light ion target designs and simulations. Recent simulations from LLNL, using the modeling developed for NIF, predict adequate gain for ion-beam indirect-drive targets. These simulations are supported by a wide variety of data from the NOVA laser at LLNL. Much-of the detailed experimental evaluation of the prospects for ion-driven ignition and gain must await results from NIF. In the meantime, development of indirect drive target designs for NIF, which are ion-beam relevant, should continue.

4.) Additional Science & Technology Questions.

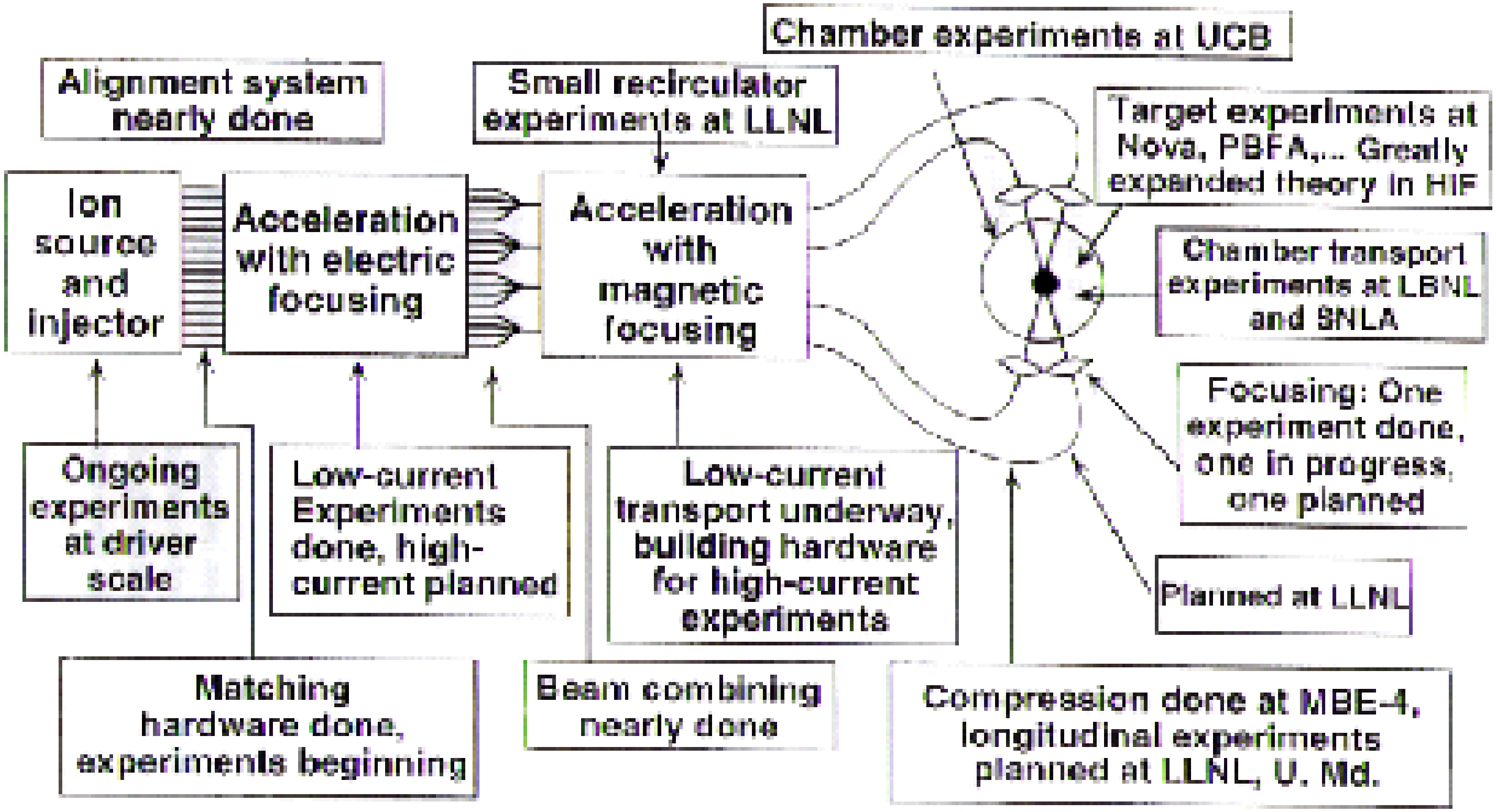
a) *Focusability*: The ability to maintain beam quality (focusability) at high current is the principal scientific challenge for the development of HIB drivers. In addition to the topics and progress noted in section I above, some additional physics issues worthy of consideration include:

(i) The goal of developing a capability to do "end-to-end (of the accelerator)" simulation of beam propagation is expected to play a key role in optimizing the MJ driver design. A linear driver will pass the beam through of order a thousand lattice periods. Therefore, experimental validation of code accuracy over long times will be important. Existing particle-in-cell (PIC) methods have shown good agreement in short experiments, and have been used to obtain converged results over hundreds of lattice periods. However, maintaining a sufficiently low noise level for long-time accuracy will be computationally challenging. The much longer beam path in a recirculator driver makes it even harder to model. Intermediate tests of understanding in this key area of long-time transport are expected to come from the small recirculator experiments (of order 300 lattice periods) and possibly more efficient "reduced" description simulation methods. Experimentation should help to determine whether piecing together results from separate analyses of carefully selected elements/accelerator modules is adequate to accurately describe an entire machine.

(ii) The physics and feasibility of self-pinched propagation in the chamber remains an important and open issue. Experiment/theory tests on this subject would be valuable.

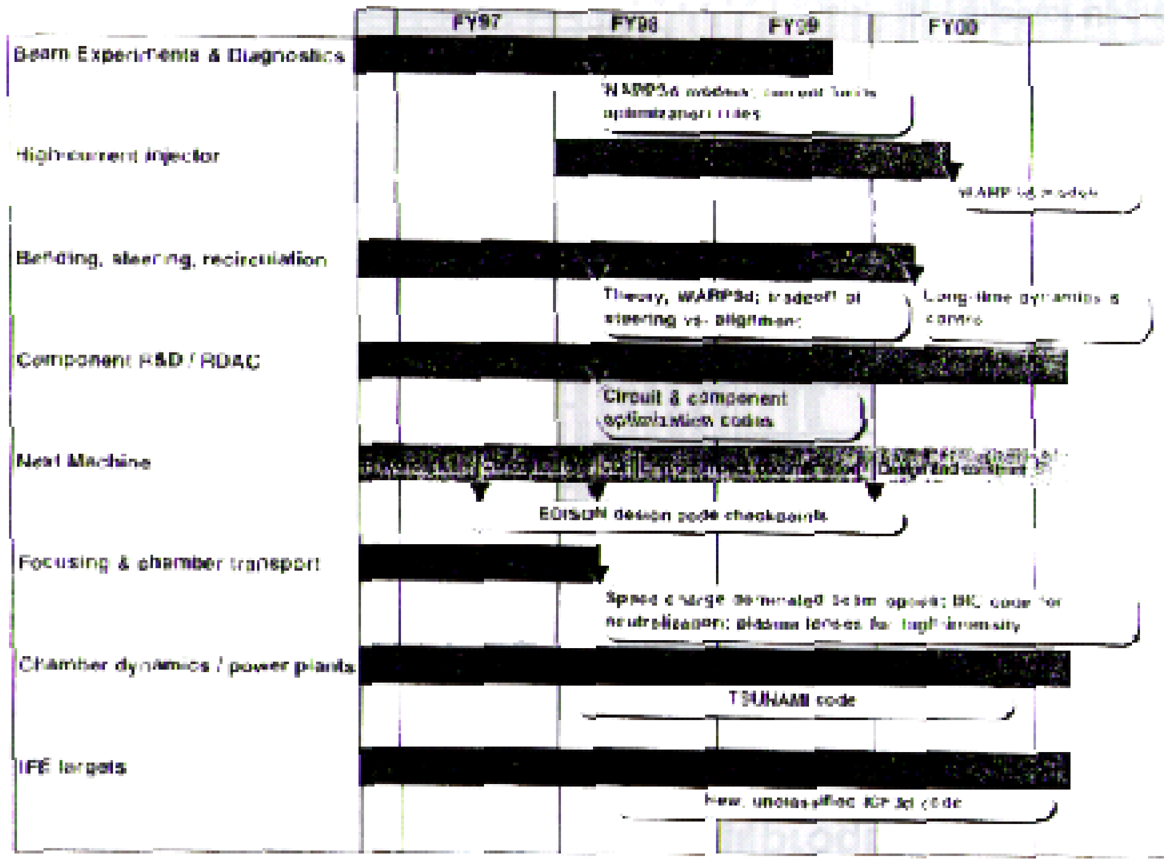
(iii) The filamentation of an HIB driver for ICF is an important issue that could benefit from some reexamination. Earlier studies [E. P. Lee, et al. Phys. Fluids 23, (1980) 2095] considered the growth of filaments in a charge-neutralized ion beam propagating through a resistive plasma medium. They concluded that filamentation required higher pressure than the ~ I mtorr present in current fusion chamber designs. Although these results are reasonable, powerful new computational capabilities can profitably be used to examine higher density regimes of interest. b.) Beam-target interaction: Intense radiation from the target, produced when the target is heated by the early time portions of the beam, can affect propagation of the remainder of the beam. Langdon et al's calculations [A.B.Langdon, Nucl. Instr. and Methods in Physics Res. A 278, p 68, 1989, and also Carlo Rubbia, Nucl. Instr. and Methods in Physics Res. A278, p 253, 1989) indicates that "photoionization of half the beam by the time it propagates to within 20 cm of the target is likely." A later more accurate kinetic calculation following a slice of ion beamlets, as they merged and hit the target, showed a 5% loss of ion deposition within the intended 3 mm radius spot (A.B.Langdon, Particle Accelerators, Vol. 37-38, p 175-180, 1992). This calculation assumed no neutralization due to collisional effects and photoionization of vapor in the chamber. Such neutralization effects further reduce the electric field and the trajectory changes. This issue should be included in the examination of all potential focussing schemes.

Experiments addressing nearly all subsystems and manipulations are in progress or are being designed

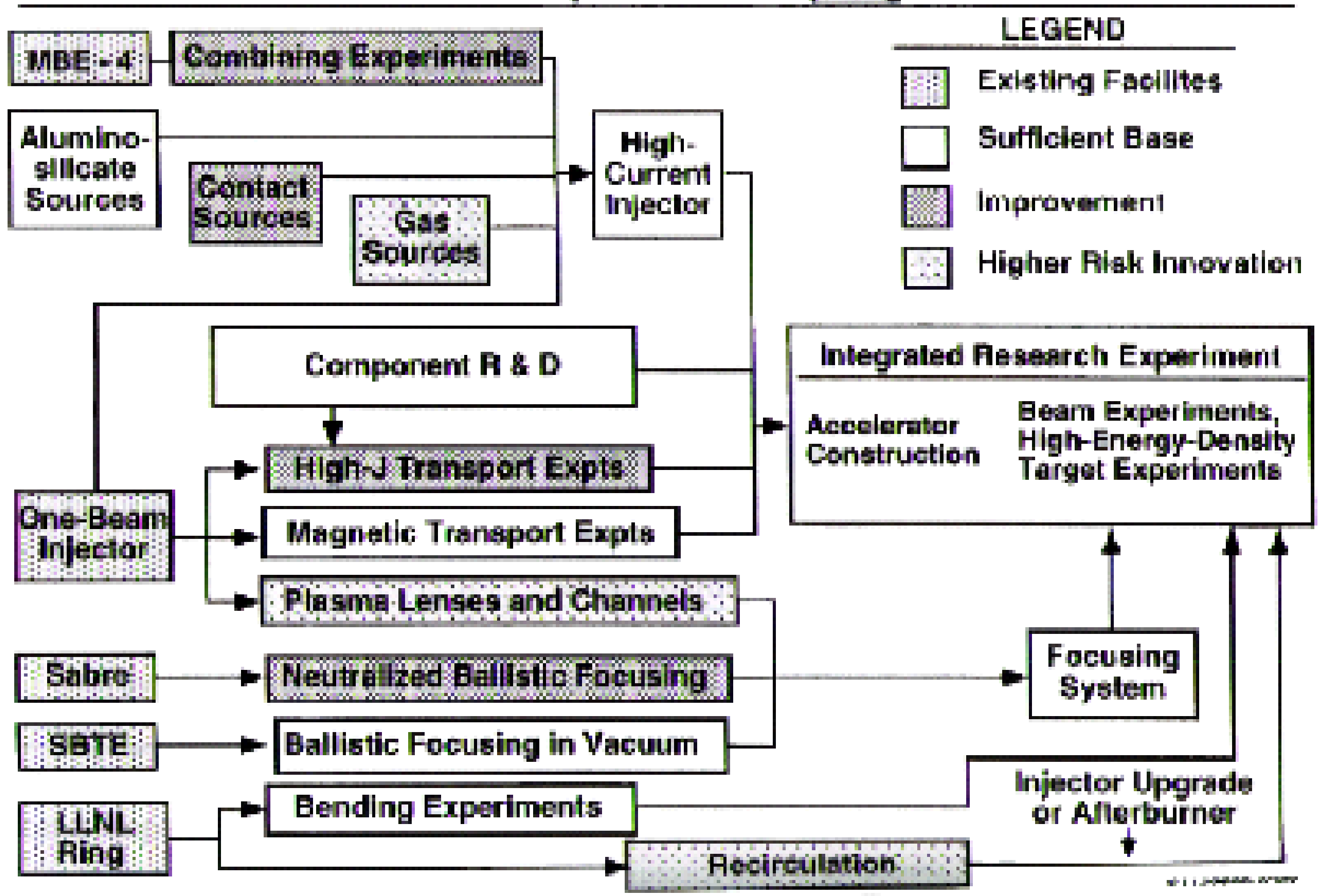


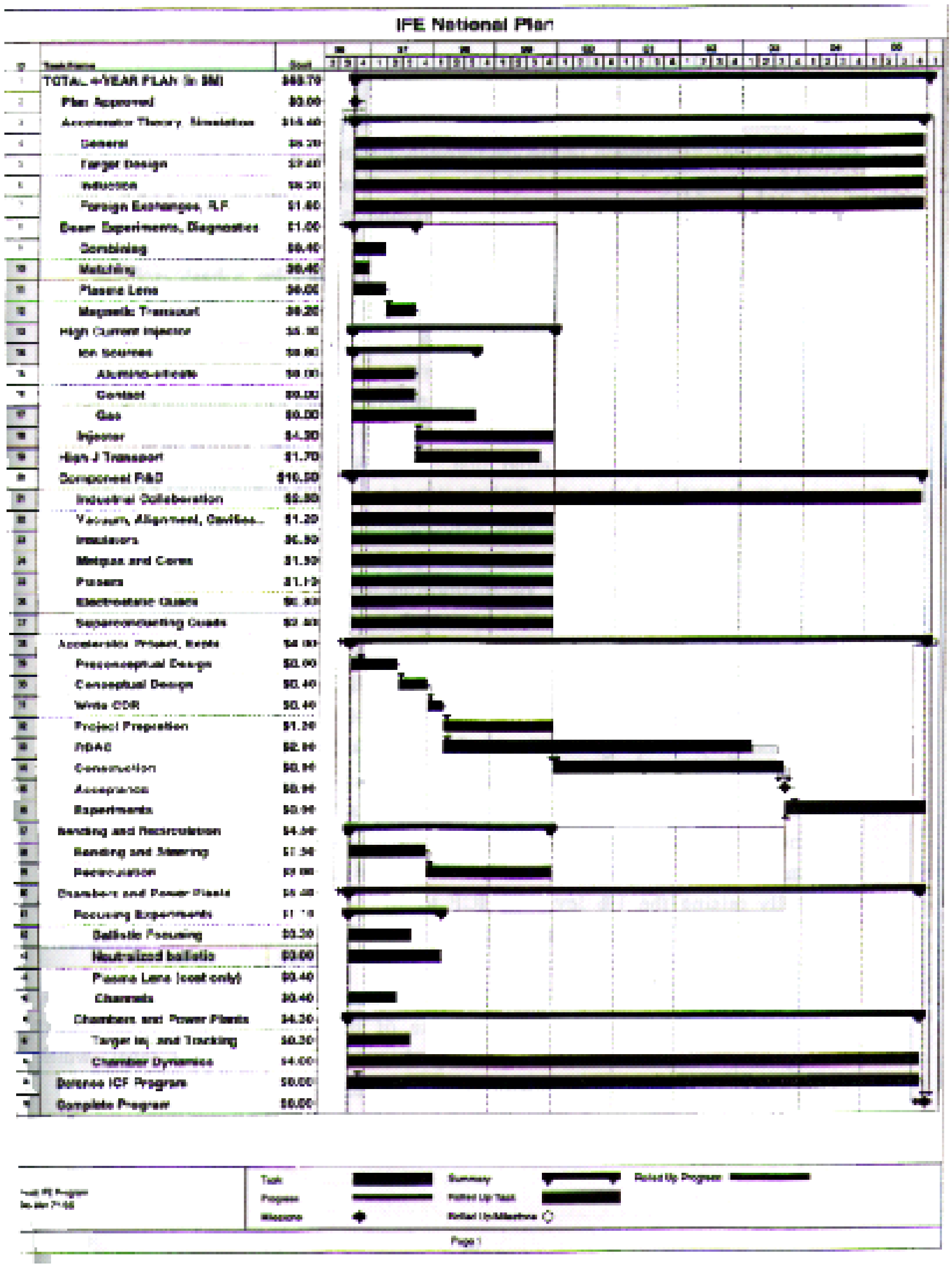
These scaled experiments do not have enough current or length to address some important issues.

Key validations of theory and simulation



Structure of near-term experimental program





C. A European Perspective. Ingo Hofmann, GSI Darmstadt.

At GSI Darmstadt (a major German national laboratory in heavy ion nuclear and applied research) there exists a laboratory commitment to develop heavy ion drivers and beam physics as well as plasma physics experiments (with heavy ions) towards the goal of IFE based on the RF Linac & Storage Ring concept. This is complemented by a basic science program funded by the Federal Ministry of Research on "High Energy Density in Matter" since 1980 (beam plasma experiments, target theory and driver development), which supports primarily University groups, again with GSI in a lead lab role. Both programs add up to approx. 2 Mio. DM/y. [An addendum: as far as tin relatively "low-level" funding of FHF in Europe one should keep in mind that, generally, salaries of scientific staff are not included and that the GSI facility is a large investment (300 Mio. DM) which came from other sources].

In other European countries (except Russia) there are smaller groups and individuals in a number of institutions who work on different aspects of HIF. I estimate these efforts as presently < 0.5 Mio. DM/y. The feasibility study proposal "Ignition Facility" submitted to the European Union would allow establishment of a formal European collaboration within the "keep-in-touch" position towards ICF (in total 1% of the yearly 200 million ECU fusion budget). Although a "Study Group" has been inaugurated in March 1995, the decision on behalf of the EU is still pending. It should be mentioned here that the report of the recent ESTA (European Science and Technology Assembly) working group, established by the previous Commissioner for Energy Research as a consulting body, was in favour of gradually raising the 1% level for ICF to 10% of the total fusion budget. This is to be seen in part as a consequence of the US declassification in energy related ICF.

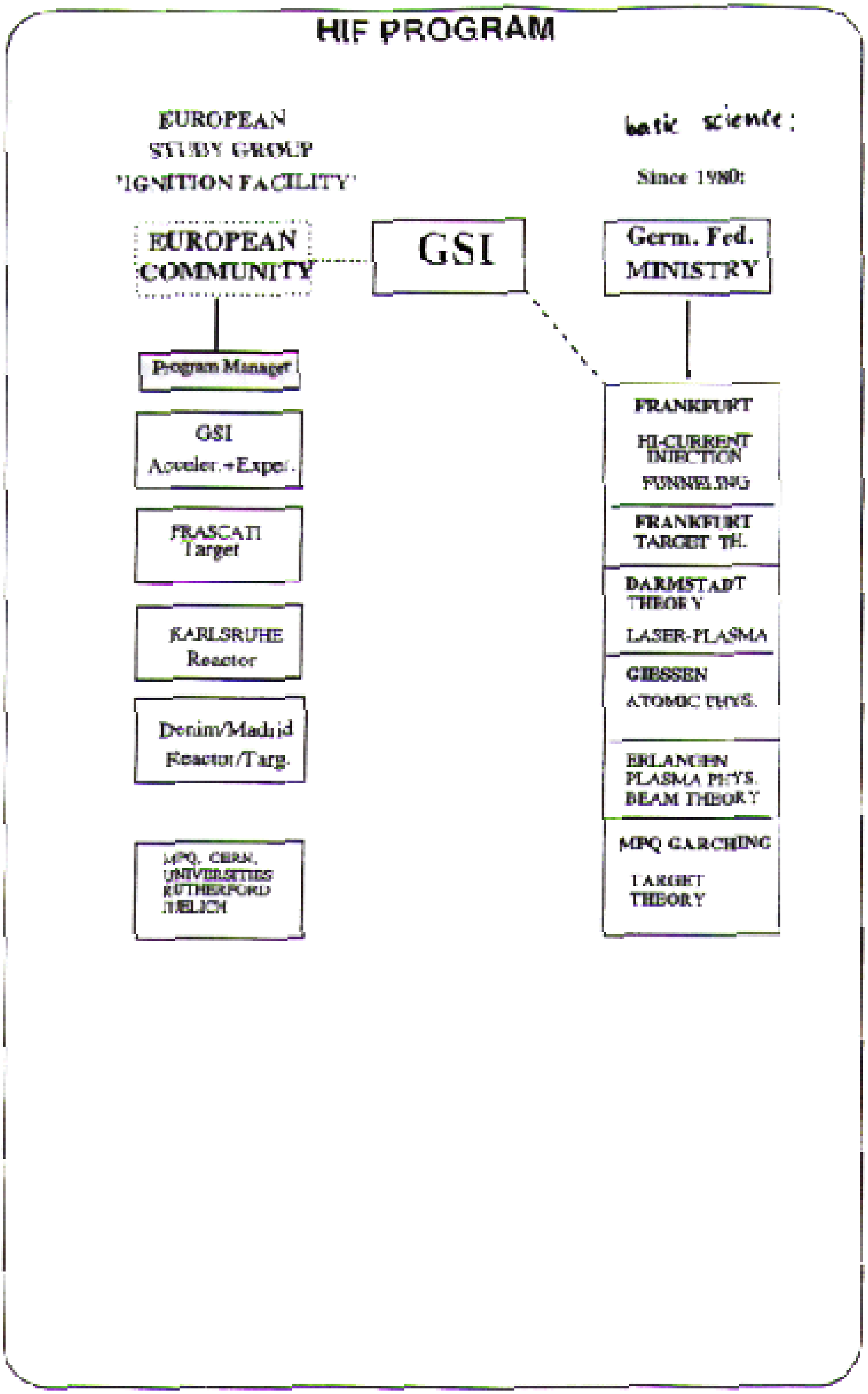
In Russia there is a collaboration between Arzamas (their former weapons lab) and ITEP/Moscow with the purpose of using the existing proton/heavy ion synchrotron at ITEP for target experiments at the kilojoule level, which requires some hardware extension to implement a foil stripping device. According to unofficial information this project expects funding at the $10 million. level (in total).

2. Technical Prospects RF vs. Induction Approach

The RF approach is based on broad experience with linacs and storage rings, however not under the extreme beam power density conditions required for HIF. In the European Study we are not yet in a position to say how many storage rings and final beam lines are really needed for a reactor driver. The induction approach is highly innovative and appears to have a larger cost saving potential due to its very high current capabilities. Since both schemes are still in a research phase they need to be pursued as complementary approaches. There is a lot of synergism which opens possibilities for effective collaboration in a number of beam physics issues, including final focusing.

3. Beam Physics - a Science?

In my estimate the LBNL/LINL beam physics group is doing excellent work and has developed capabilities which are unique in their kind. The codes are used under the special technical boundary conditions of injectors and the induction accelerator, where they have developed an extremely high standard of modeling. Applying their 3-D simulation tools to areas of concern in the larger accelerator community (including the RF approach to HIF) would be an excellent opportunity to foster the links with the broader field and give the group the recognition it truly merits. At the same time, confidence in their simulation tools would build up in the accelerator community. I believe that it is largely the detachment from too specialized an accelerator environment (especially at low energy) which is a condition for recognition of beam physics as science.



D.

Integrated Research Experiment.

The overall objective of an Integrated Research Experiment (IRE) is: to provide the capability to investigate the science of heavy ion beam/target interactions; and to provide a data base that, together with the results from the broadened base program and NIF, will be sufficient to support a decision to proceed with the construction of a full scale heavy ion IFE driver. The design parameters for this proposed experimental facility are not fixed at this point, although a number of representative examples of facilities at about the right scale have been studied in the past.

The overriding issue in the development of heavy ion accelerators is the transport and beam control of very high power, high brightness ion beams. The generation, axial compression, and merging of multi-beam, high-current, heavy ion beam pulses in the presence of strong electromagnetic interactions with the accelerator structures must be carried out, while maintaining a good beam emittance (brightness). There are no fundamental impediments, but it is clear that a variety of passive and active beam control systems are needed. Experiments at the scale of the IRE are essential to develop the experience and understanding needed before a fail scale driver can be designed with confidence. The induction accelerator technology has demonstrated adequate reliability, rep-rate capability, and efficiencies in moderate scale experiments. The main issue in the technology area is achieving these performance capabilities at a low enough cost to meet the economic goals.

The committee concurs with the IFE Program's description of the science and technology elements that should be included in this integrated experiment:

- The IRE should provide the experimental capability for resolving the basic beam dynamics issues involved in the generation, acceleration, and pulse compression of a heavy ion beam, through the accelerator and through the beam transport to the target chamber.

- It should be capable of studying experimentally a wide range of schemes for focusing and transporting the heavy ion beam onto the target, including vacuum ballistic transport, plasma neutralization, plasma channel transport, and self-focused transport.

- It should provide an experimental evaluation of energy deposition and target heating with heavy ion beams in hot ionized matter, in the temperature regime of a 100 eV or more, including any effects that radiation from the target might have on the focusing and steering of the ion beam passing through various background gases in the target chamber.

- The operation of this facility, at a rep rate of several Hz, will also provide engineering data on the efficiency, reliability, and costs at a scale that will allow meaningful extrapolation to a full scale induction linac driver.

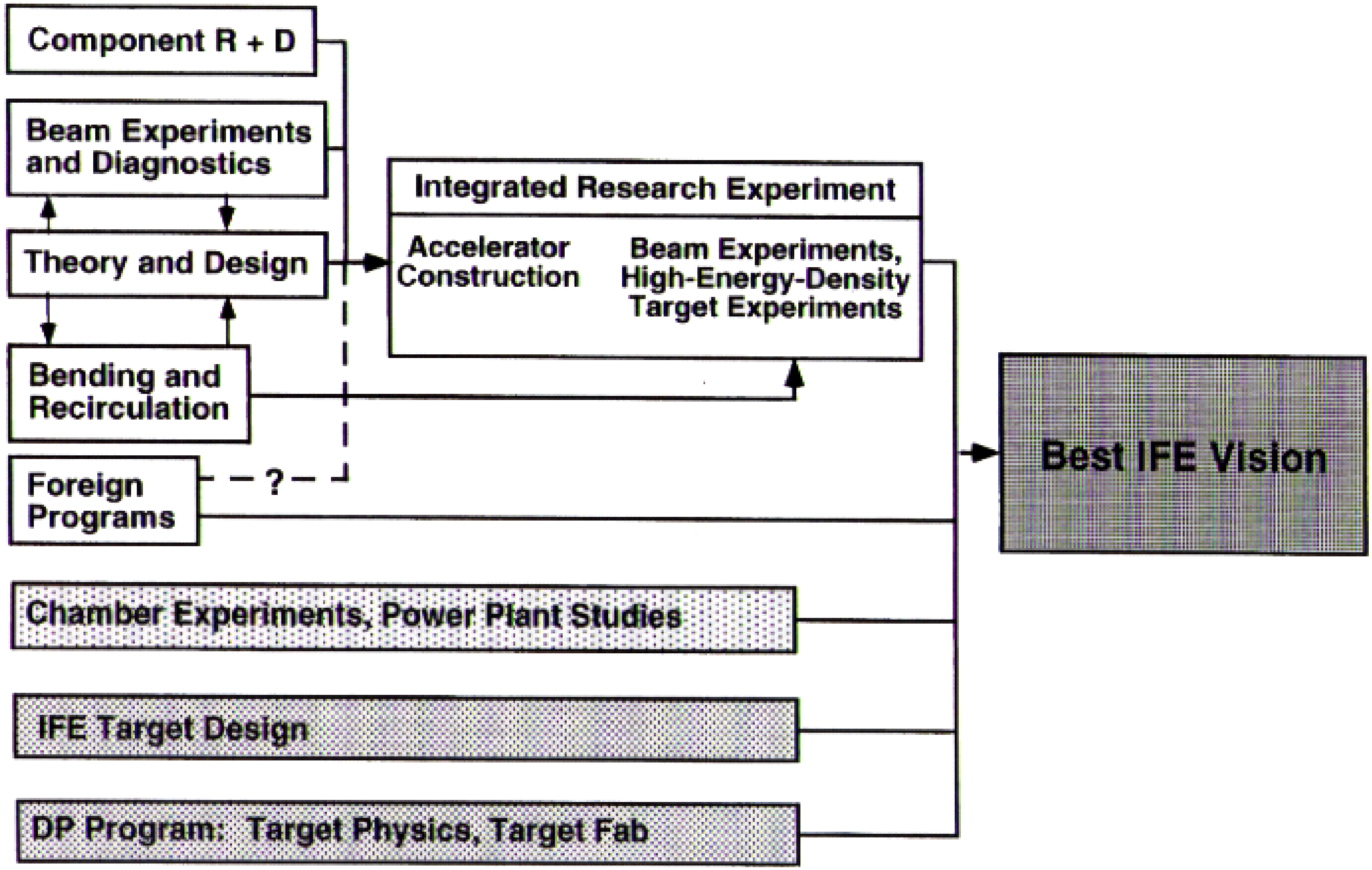
To achieve these objectives, the IRE should be designed with the flexibility for experimental studies over as wide a range as practical, both in the operational modes of the beam in the accelerator as well as the beam parameter variations possible for final focusing, transport, and target heating studies. For example, with plasma-based ion sources, a range of ion masses is possible in principle, if the appropriate flexibility is provided in the beam transport system.

The challenge faced by the IFE Program in the design of the IRE is how to achieve these objectives at an affordable cost. The general parameter range under consideration is a pulse energy in the range 3 to 30 kilojoules, at a beam voltage of 100 to 300 MeV (with singly charged K, for example). At a pulse length of order lOns (after compression, at the target) the beam current is several kiloamps. The beam current in the accelerator should then be several hundred amps, sufficient to reach the "heavy" beam loading regime necessary for high efficiency operation of the accelerator cells. It is also necessary to be in this regime to fully evaluate the longitudinal dynamics of the beam in the presence of significant feedback from beam loading of the accelerator cells. This feedback is especially important in understanding the amplification of current waveform fluctuations (klystron-like bunching modes), and the viability of various correction schemes for maintaining smooth pulse waveforms.

To accurately model the phenomenology of a full-scale driver in a machine that is about 10-20 x smaller, scaling of several of the key parameters is necessary. Major variables that have a significant effect on the cost include the final beam voltage, the pulse length (or the joules in the pulse), and the ion mass. Over the next two years, trade studies to identify the most promising parameter sets for the IRE should have a very high priority.

Previous designs of a so-called "High Temperature Experiment" (HTE), with many of the same objectives, explored a similar parameter regime, see for example, "Accelerator Inertial Fusion -- A National Plan for the Development of Heavy-ion Accelerators for Fusion Power", Los Alamos National laboratory Report LA-UR-81-370, Dec. 10, 1981, and "Heavy Ion Accelerator Research Plan for FY84-FY89", Los Alamos national laboratory Report LA-UR-83-1717, May 1983.

IFE Program Structure



01130696-0301

E. Progress on potential laser drivers for IFE.

Both KrF and Diode-Pumped Solid-State Lasers (DPSSL's) have potential as drivers for IFE. Although both laser systems have projected laser efficiencies of less than 10% for IFE applications, the projected target gains for Direct Drive targets could be high enough for economical energy production. Although quite speculative, the potential enhanced gain of direct drive targets ignited by a fast ignitor laser beam could further relax the laser efficiency requirements, or reduce the laser energy required for IFE.

Since 1993, significant progress in the ICF Program has been made in developing both the target physics and technology required for Direct Drive IFE with lasers . The NIF is being designed to allow testing of Direct Drive targets. Programs to establish the laser requirements for laser beam smoothing and hydrodynamic instability control are being actively pursued on the recently completed Omega glass laser at the University of Rochester and the KrF Nike laser at the Naval Research Laboratory.

The 60 beam Omega laser is capable of delivering 30-45 KJ of laser light at 0.35 mm in a flexible pulse shape. Omega is the principal U.S. facility for exploring direct drive implosions and will be used for establishing the requirements for direct drive ignition on the NIF.

The 56 beam KrF Nike laser can deliver 2-3 kJ of energy at 0.248 mm. to planar targets. Nike will be used primarily for the study of imprinting (target perturbations created by laser intensity variations in the laser beam), and subsequent hydrodynamic instability growth. Individual Nike beams have achieved spatial intensity uniformity of about 1% when averaged over the 4 ns duration of the laser pulse. This a factor of several better than can currently be achieved with glass lasers although improvements planned for Omega are expected to significantly improve its beam quality.

System studies of KrF lasers have concluded that 5-7% efficiency is feasible (perhaps somewhat more if waste heat from the amplifiers is recovered). The Nike laser, which was not designed for efficiency or high repetition rate, operates at about 1.7% efficiency. For IFE, amplifiers would need to be developed which demonstrate the required efficiency, repetition rate and durability.

Flashlamp-pumped Solid-State lasers do not have the efficiency or heat handling capability required for IFE. For example, the NIF, as designed, will operate at about 1/2 % efficiency. However, solid state lasers which use a gas-cooled crystal gain medium, pumped with efficient diode lasers have projected efficiencies near 10%. Many elements of such a system have been demonstrated on a small scale at LLNL. A 2 joule DPSSL at LLNL, which used the crystal Yb:S-FAP as the gain medium, has operated at 25 Hz with gas cooling and has demonstrated an ability to handle heat fluxes in excess of those required for IFE. Larger scale DPSSL lasers would take advantage of the technology developed for the NIF. A major issue for DPSSL's is the cost of diodes. For IFE applications, diode costs of $ 0.10/watt or less are required. Current diode costs are about $10/watt, and the cost goal for diodes to be used on the NIF is $1/watt. Diodes have a variety of commercial and military applications and their price is projected to decrease as these markets grow.

A generic issue for laser IFE is protection of the final optics against neutrons, X-rays, and debris from the target and chamber. Grazing incidence metal mirrors (GIMM's) and self-annealing fused silica optics operated at several hundred degrees Centigrade have been proposed as solutions. An OFES sponsored program to further evaluate possible optics protection approaches could help establish criteria for determining laser requirements.

DP is supporting a modest development effort on DPSSL's and a research program on the fast ignitor. At present there is no funding for KrF rep-rated high power amplifier development. Although we are not recommending an OFES program on laser driver development at this time, we do recommend that

OFES continue to evaluate progress on laser drivers and direct drive targets in DOE Defense Programs. We also recommend that OFES act to encourage international collaborations with the U.S. on laser driver developments directed toward IFE.

F. IFE Power Plants (Progress and Needs)

A number of excellent, comprehensive, conceptual design and system studies for IFE power plants have been completed over the last few years. Innovative concepts have been developed through these studies, and they have contributed to providing a greater understanding of the prospects and issues for IFE. These studies have shown the promise of IFE as a competitive energy option. The key technical issues, derived from this work, are listed in Table 1.

The target physics and performance, and target-beam interactions will be addressed primarily by the DP program, partly in the R&D for NIF, and then through experiments on NIF.

Several issues affect the viability of fusion chamber designs for IFE. The first issue concerns the feasibility and performance of a viable wallprotection scheme. A practical IFE system requires protection of the solid chamber wall from rapid degradation due to the extremely high instantaneous heat and particle loads associated with the X-rays and debris from the target explosion. While researchers agree on the need to protect the solid chamber wall, there is no consensus on the best means to achieve this. The two leading schemes proposed for wall protection are : 1) thick liquid layer, and 2) thin liquid layer. In the first scheme, a thick layer of a liquid, e.g. flibe, is formed inside the chamber solid walls to form a "pocket" surrounding the microexplosion. This scheme has the added advantage of also protecting the first wall from neutron damage. Examples of key issues associated with this scheme are:

1) the ability to form a stable and uniform thick liquid layer so as to fully cover the interior surfaces of the first wall,;

2) the feasibility of forming the liquid layer so as to allow holes for the driver beams without exposing the first wall to unacceptable levels of X-rays and debris;
3) the ability to re-establish the wall protection layer after the microexplosion; and
4) the need for this liquid to contain lithium to provide adequate breeding and the ability to clear the chamber from a multi-species liquid (e.g. the molten salt flibe).

Another scheme for wall protection relies on a thin liquid metal film wetting the first wall. This concept allows greater control over liquid feeding and uniformity of the liquid layer. It can use a single-element liquid; for example, lead, which is a neutron multiplier that can also enhance tritium breeding. Examples of issues with this scheme are: a) blast effects, b) flow around geometric perturbations, c) neutron damage and activiation, and d) protection of inverted surfaces. Only a very small effort has been devoted to this critical issue of wall protection. Experiments and modelling are needed to evaluate the scientific and technological issues - fluid mechanics, thermomechanics, and materials response - of the various wall protection schemes

The second IFE issue is cavity clearing at IFE pulse repetition rates. Following each pellet explosion, the cavity (chamber) fills with target debris and material evaporated or otherwise ejected from the cavity surfaces. This material must be removed from the cavity before the next target is injected. This generally requires recondensing condensable gases onto the surfaces of the first wall (or more specifically the surfaces of the wall protection layer) and by pumping non-condensable gases out through large ducts. Power reactors require a repetition rate of -3-10 pulses per second. Evacuation requirements depend on propagation limits for both targets and driver energy. Base pressure requirements: determine 1) the time to evacuate the chamber; and 2) the level of protection to the first wall (and final optics) afforded by the cavity background gas. Research is needed to better understand clearing requirements, the recondensation process, and to develop design solutions. Some small scale experiments are being planned at universities.

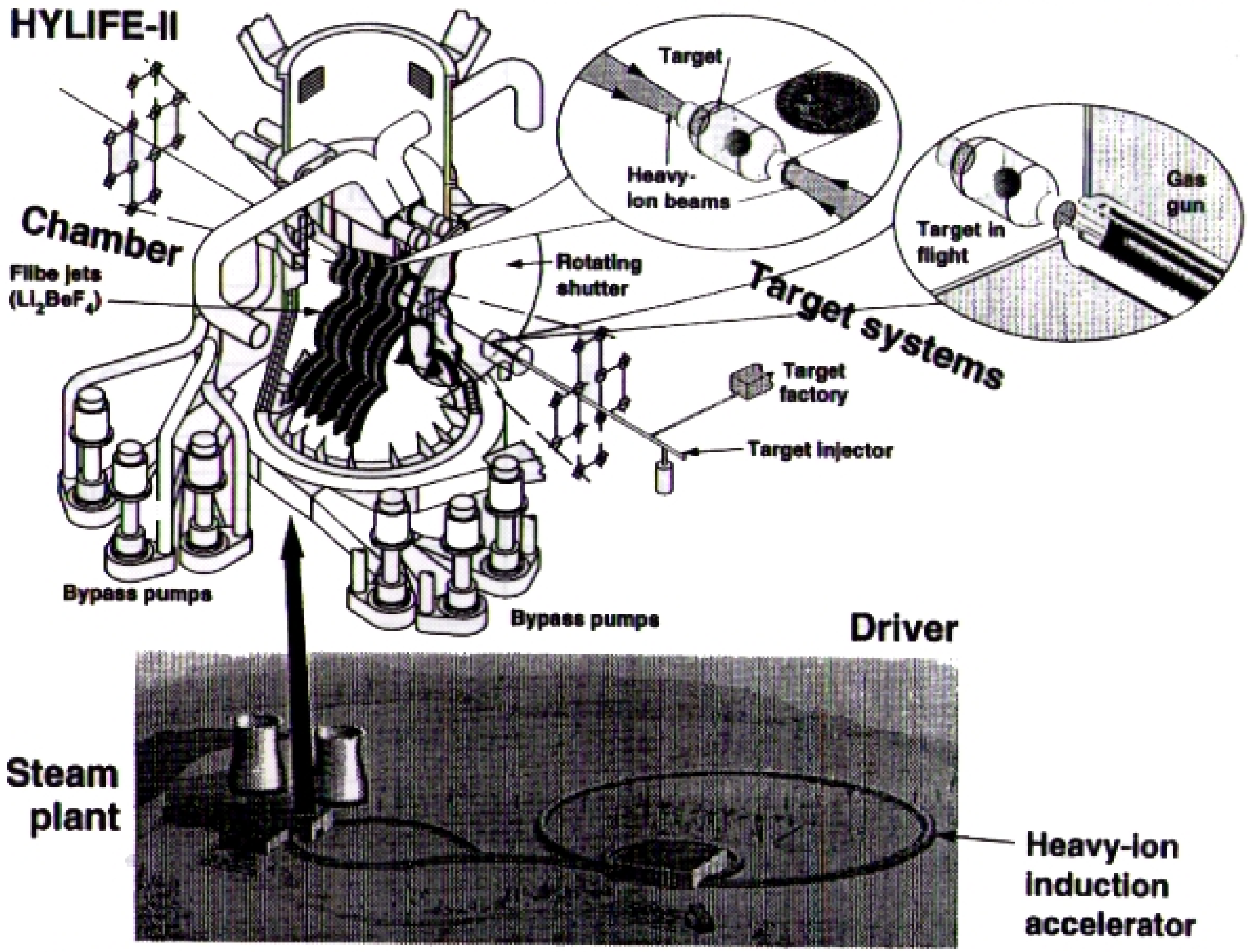
The remaining fusion chamber and target fabrication issues in Table I are related strictly to power plant technology feasibility, safety, and economics. They include: demonstration of tritium self-sufficiency in a practical IFE system; demonstration of adequate radiation shielding of all components; thermo-mechanical response and radiation damage of the first wall/blanket; and demonstration of low cost, high volume target production techniques. The required R&D and the resolution of these last four issues will be greatly influenced by the results of research to resolve the previous issues.

Table 1

Top-Level Issues For Inertial Fusion Energy

1	Sufficiently High Target Gain at Economical Driver Size: a) G > 30 for indirect drive with ion beams. b) G ~ 100 for direct drive with lasers.
2	Driver cost, efficiency, reliability, and lifetime: a) Demonstration of the required performance of a driver operated in a repetitive mode. b) Performance, reliability and lifetime of final optics.
3.	Fusion Chamber: a) Feasibility and performance of a viable wall-protection scheme. b) Cavity clearing at IFE pulse repetition rates. c) Tritium self-sufficiency in a practical IFE system. d) Adequate radiation shielding of all componenets. e) Pulsed radiation damage and thermomechanical reponse of first wall/blanket, particularly for concepts without thick liquid protection.
4.	Sufficiently low cost, high volume, target production system.

A number of integrated IFE power plant designs exist



Liquid-jet protected fusion chambers for long lifetime, low cost, and low environmental impact

G. Synergy of IFE/ICF and MFE.

- There is an important synergy in plasma theory and computer modeling as seen in the numerous books on plasma physics; e.g., in such areas as Particle -in -Cell simulations and intense radiation plasma interactions

* Non-linear plasma instabilities, shock waves and implosion codes, nonneutral plasmas, plasma-wall interactions, and intense ion-beam physics are important common interests

- There is much in common in atomic physics and diagnostic needs, notably in the radiation detection area-mirrors, photo-detectors and lasers.

- Common technology interests include neutron damage resistant materials development and tritium breeding blanket technologies.

The IFE Program is synergistic with other DOE programs

IFE TASK	MFE	Other ER	ICF	Other DP	Other DOE
Theory, Simulation, Small Experiment	PS	HENP	PS, TD	RAD	HAP
High Current Injectors and Transport	NBH, MT	HENP, SNS	HED	RAD	HAP
Ion Sources	NBH, DIAG	HENP, SNS	HED	RAD ?	HAP
Components			HED		
Electrostatic Quadrupoles	NBH	HENP, SNS			
Magnetic Lenses	MT	HENP, SNS		RAD	HAP
Pulsers	MT	HENP, SNS		RAD	HAP
Magnetic Materials	MT	HENP, SNS		RAD	HAP
Insulators	NBH, MT	HENP, SNS		RAD	HAP
Integrated Facility		HENP, SNS	HED	RAD	HAP
Bending and Recirculation	PS	HENP	PS		
Focusing			HED, LIF		
Chambers and Power Plants	MR		MR		HAP

BNCT = Boron Neutron Capture Therapy, DIAG = Diagnostics, HAP = High Average Power (e.g.waste management), HED = High Energy Density Physics (creates LMF option?), HENP = High Energy and Nuclear Physics (e.g. relativistic klystrom), LIF = Light Ion Fusion, MR = Materials Research, MT = Materials Testing, NBH = Neutral Beam Healing, PS = Plasma Simulation, RAD = Radiography, SNS = Spallation Neutron Source, TD = Target Design.

Charge to to Fusion Energy Advisory Committee
for an Inertial Fusion Energy Review

Since 1990 to fusion program has had a mandate to pursue two independent approaches to fusion energy deveopment magnetic mid inertial confinement fusion. In magnetic fusion, our strategy in to continue to use international collaboration, especially participation in the International Thermonuclear Experimental Reactor, to pursue fusion energy science and technology. In inertial fusion, our strategy has boon to assume the target physics is the highest priority activity and would be developed as a part of the weapons research program; arid. indeed the next step in the development of target physics, namely the National Ignition Facility is proceeding into construction in Defense Programs.

Based on the Fusion Poky Advisory Committee report of 1990, we had token as our highest priority in inertial fusion energy the development of heavy ion acceleration; as the most desirable driver for energy applications. That development program has met all of its milestones and has received numerous positive reviews, including one by the Fusion Energy Advisory Committee (FEAC), which in 1993 recommended a balanced Inertial Fusion Energy program of heavy ion accelerator development plus other smaller scale efforts, at $17 million per year.

The potential for inertial fusion energy has been judged to be real, but the fusion program no longer has as a goal the operation of a demonstration power plant by 2025. Given that the basic mission of the fusion program has changed from energy development to fusion energy science. and that funding for the entire fusion program will be constrained for some number of years, I would like FEAC to again consider inertial fusion energy and recommend what to new Fusion Energy Sciences program should be daft in support of this future fusion application and at what lover?

Fig. 7 shows the analytically estimated gains[10] (as a function of ion beam focal spot radius for two typical heavy ion ranges) for targets with locahzed radiators such as those in Fig 6a. These calculations are based on capsule designs being developed for the NIF, and data on radiation transport and hohlraum energetics obtained from Nova experiments. Also shown in Fig. 7 are the capsule energies and required hohlraurm temperatures. Capsules with the smallest energy indicated, 0.2 MJ, can be directly tested on the NIF. Symmetry is obtained in these localized radiator designs by using symmetry shields to remove long wavelength variations in the radiation flux. Similar approaches to controlling symmetry have been successfully tested on Nova[3]. As shown in Fig. 7, the gains are critically dependent on the spot size of the ion beam when it is focused on the target radiators. The HI driver energy required to drive a fuel capsule of a given size depends inversely on the efficiency with which the ion beam energy is converted to x rays. This in turn depends on the focal spot size and range of the ions which determines the mass of material heated by the ions. As the ion range is reduced, less mass is heated for a given spot size. This results in a higher gain for a given spot size or a larger tolerable spot size for a given gain. For idealized radiator designs, 50-80% of the driver energy can be converted to X-rays[1]. Recent more detailed calculations which include full radiation transport and radiator wall motion obtain conversion efficiencies of about 50%. These calculations indicate the radiators with very -small spot sizes are likely to suffer from closure due to wall motion. More work is required to fully optimize radiatior designs for these localized radiator designs. The targets in Fig. 7a are readily adaptable, in principle, to single sided irradiation. If the radiators are constructed with a 90 degree bend prior to entering the hohlraum, the ion beams can come in from a single side while maintaining basically two-sided axisymmetric irradiation of the capsule.

4.2 Distributed Radiator Designs - Two-Sided

The distributed radiator design shown in Fig 6b, is suitable for relatively short range ions. This design uses the same capsules as the localized radiator design and NIF, but symmetry is obtained by locating the radiating material where it is required for symmetry. This can be achieved by varying the density and radiator material. Fully integrated design calculations, similar to those that have been done for NIF targets, have been successfully carried out. Fig 8 shows the materials and densities used at the beginning of a particular series of calculations which achieves adequate symmetry and gain of 40 with about 7 MJ of 3.5 GeV Pb ion beam energy[12]. This design uses low density high-z materials for the hohlraum wall in order to maintain near pressure equilibrium between the walls and the foam radiator material. Fig 8 also shows the density contours near peak compression. Such calculations have been made possible by the developments in modeling for the NIF but much less effort to date has been devoted to optimizing the HI targets. When optimized, targets like those in Fig 8 are expected to have gains of 50-70 when drive by 5-7 MJ of ions. Integrated calculations are also being carried out on the localized radiator designs, but these designs have complicated hydrodynamics in the radiators and internal symmetry shields which has not been fully modeled.

4.3 Spherical Target Designs

A range of "symmetrically" irradiated targets such as the target shown in Fig 6c, is also feasible. The potential gain of these targets depends on the degree of "direct coupling" of the ion beam to the fusion capsule. Two designs which indicate the range of target sizes and gains are shown in Fig. 9. The light ion program at Sandia National Laboratories (SNL) has examined the design shown in Fig 9a. In this design, the ions are absorbed entirely in the high-z shell and the low density foam outside the fuel capsule[13]. The high-z shell and foam produce x rays which then implode the fuel capsule. The capsule design is largely similar to the NIF target designs, with the exception that the Sandia design has an outer layer of BeO to help provide "internal pulse shaping". This layer can help relax the accelerator pulse- shaping requirements. Because there must be enough material to stop the ions over then entire surface of the target, there is a larger heat capacity of radiator material in these spherical targets than in two-sided designs. This results in lower x-ray production efficiency, and relatively low gain at a large driver energy.

The other extreme in symmetrically illuminated targets is the direct drive target ion target In the example indicated in Fig. 9b., the pressure which drives the implosion of the DT layer is generated in the CH2 layer which is directly heated by the ion beams[14]. At early time, there is very little smoothing of nonuniformities, which arise because of the overlap of a finite number of ion beams. At later times in the pulse, the CH2 generates enough radiation that radiation smoothing is significant. If sufficient uniformity can be achieved[15], such targets can have very high gain for relatively small drivers. Because both the symmetry and hydrodynamic instability characteristics of this target depend sensitively on details of the ion beam and the illumination geometry, relevant experiments will require a significant scale ion beam machine with many beams.

A 3D radiation transport capability is probably required to accurately calculate the number of ion beams required for symmetry in both of the above designs. The Indirect Drive symmetric target will require fewer beams than the directly driven design. Using a 2D diffusion approximation, SNL has estimated that 12-20 beams will be adequate for their target design. Full transport calculations in 2D are now possible. Further development of the 3D codes mentioned above, planned for next few years, will allow 3D calculations of these ion targets.

4.4 Ion Beam Coupling Experiments

The issue of x-ray production using ion beams is currently being addressed by experiments on the PBFA 11 light ion accelerator at SNL. On PBFA, 1-2 TW/cm^2 lithium ion beams have been focused on conical gold targets filled with low-z low density foam. Although the temperature achieved in. these experiments is less than 100 eV, the measured radiation temperature and x-ray spectrum, as well as the tamping of the gold wall expansion by the foam, are in agreement with calculations. LASNEX calculations indicate that fusion relevant matter conditions can be achieved with a heavy ion accelerator delivering as little as 1 KJ of energy Experiments at GSI Darmstadt have produced a 400 nun diameter focal spot using an approximately 10 cm focal length z-pinch plasma focus. Using this focal diameter, LASNEX calculations, using I KJ of ions with a range of 0.03 g/cM^2 delivered in 2 ns, predict temperatures of 250 eV in a gold lined Be cylinder. A wide range of experiments could be carried out with such plasmas. The effect on beam focusing of photo-ionization of the incoming ion beam, caused by target radiation emission, could readily be addressed.

5. Direct Drive Laser Targets for the NIF

Although Indirect Drive is the baseline approach to ignition and gain on the NIF, sufficient progress has been made on Direct Drive with lasers over the past 3 years that the NIF the target area is also being configured for Direct Drive as shown in Fig. 10. By moving 24 of NIF's 48 beam clusters, it is possible to achieve the geometric irradiation uniformity of better then 1% required for Direct Drive. The proposed beam arrangement is shown in Fig. 10. The geometric placement of the laser beams, as well as beam power balance and pointing accuracy primarily affects the long wavelength perturbations on the fusion capsule. This geometry is relatively straightforward to specify. The principal target uncertainties for Direct Drive are the imprinting of short wavelength perturbations onto the outside surface of the fusion capsule, and the subsequent growth of these perturbations by Rayleigh-Taylor Instability. This imprinting occurs because all techniques currently used for beam smoothing require some time to become effective. During this startup phase, residual intensity variation across beams imprint surface modulations on the target. The physics of this imprinting is quite complex and is one of the principal research topics for Direct Drive. As the target is accelerated, these modulations are amplified by Rayleigh-Taylor growth. The growth of all perturbations from both target fabrication and laser imprinting grow more rapidly for Direct Drive targets than for Indirect Drive targets of a given compressibility. This difference is related to the much higher ablation rates of Indirect Drive[3]. To reduce the growth rate of instabilities in Direct Drive, the targets are deliberately preheated. However this approach also reduces the possible gain by reducing the compressibility as shown in Fig. I I for calculations from the University of Rochesterl6. In this Fig, a is the ratio of the pressure in the shell to the Fermi degenerate pressure at the same density. The current baseline target for the NIF has a--3 with a gain of 30 at 1.5 MJ. If a scheme can be developed for reoptimizing the laser focal diameter near the peak of the laser pulse, the gain increases to about 50. Under the same set of assumptions, the gain is estimated to be 130-150 at 10 MJ. Depending on the feasible laser efficiency, this gain is adequate for energy production although the laser is quite large. The recently completed 60 beam Omega Nd-glass laser at the University of Rochester will be used to establish the understanding required to accurately specify the smoothing requirements and instability growth for Direct Drive on the NIF. The Nike facility at the Naval Research Laboratory will address these issues in planar geometry -for. a KrF laser. Direct Drive targets require a uniform distribution of beams over the entire surface of the target as indicated in Fig. 10. Unless some approach can be developed which relaxes this requirement, Direct Drive is incompatible with the protected wall fusion chamber designs discussed above. A major issue for laser driven fusion chambers is survivability of the final optics to x-rays, neutrons, and debris. This issue win be addressed to some extent on NIF, but for a much smaller number of shots than is required for IFE. Although driver beam imprinting and subsequent hydrodynamic instability growth are common issues for both ion beam and laser beam direct drive targets, the specific mechanisms for imprinting are unique to each driver. Hence the information learned for Direct Drive with lasers will not significantly increase the understanding of Direct Drive ion beam targets.

6. Fast Ignitor approach to ICF

A still more speculative approach to ICF, which has potentially high leverage for high gain, is the fast ignitor approach17. In the standard approach to ICF, fusion fuel is imploded and subsequently compressed in such a way that a relatively low density hot spot is formed in the center of a dense shell which contains most of the fuel. The hot spot must be large enough to capture the alpha particles and initiate a self propagating bum wave into the main fuel. The performance of these targets is very sensitive to the mix of cold fuel from the surrounding dense shell into the hot spot or asymmetry in the implosion, both of which can quench the bum. In the fast ignitor approach to ICF, the compression and ignition steps are separated. A conventional driver is used to compress the fuel, but no attempt is made to produce the central hot spot. This relaxes the sensitivity of the implosion to asymmetry and mix. The energy required to ignite the compressed fuel must then be delivered to the compressed core by a separate beam before the core has a chance to expand. While the compression beams can deliver their energy in nanoseconds, the ignitor beam must deliver its energy in about 10 ps into a spot of about 10 min radius. Because targets which are uniformly compressed require lower density for good bum efficiency, such targets can have a gain which is a factor of several higher than that of standard ICF targets. The achievable gain will depend on the efficiency with which the fast ignitor beam is capable of delivering its energy to the compressed core. The intensities involved in the fast ignitor pulse are 10^{19}-10^{20} W/cm^2. At these intensities, the laser plasma interaction is highly relativistic.18 A laser beam capable of delivering greater than 600 joules in 500 fs has recently been completed on Nova. This laser will be used to test key physics issues associated with delivering the ignitor energy to a compressed ICF target.

References:

1.) Fusion Energy Advisory Committee: Advice and Recommendations to the U.S. Department of Energy In Response to the Charge Letter of September 18, 1992, DOE/ER-0594T (June 1993).

2.) Review of the Department of Energy's Inertial Confinement Fusion Program Final Report, National Academy Press, 2101 Constitution Avenue, Washington D.C. (September 1990)

3.) J.D. Lindl, Development of the Indirect-Drive Approach to Inertial Confinement Fusion and the Target Physics Basis for Ignition and Gain, Physics of Plasmas 2 (11),p 3933-4024 (Nov 1995)

4.) See National Technical Information Service Document No. DE96010698 (ICF Quart. Rep. Spec. Iss.: Nova Technical Contract, UCRL-LR-105821-95-4)

5.) V. Narayanamurti, letter to Dr. Victor H. Reis, Assistant Secretary for Defense Programs, on behalf of the Inertial Confinement Fusion Advisory Committee

6.) S.W. Haan, S.M. Pollaine, J.D. Lindl, L.J. Suter, R.L. Berger, L.V. Powers, W.E. Alley, P.A. Amendt, J.A. Futterman, W.K. Levedahl, M.D. Rosen, D.P. Rowley, R.A. Sacks, A.I. Shestakov, G.L. Strobel, M. Tabak, S.V. Weber, G.B. Zimmerman from LLNL and W.J. Krauser, D.C. Wilson, S. Coggeshall, D.B. Harris, N.M. Hoffman and B.H. Wilde from LANL, "Design and Modeling of Ignition Targets for the National Ignition Facility," Phys. Plasmas 2, 2480 (1995)

7.) Krauser, N.M. Hoffman, D.C. Wilson, B.H. Wilde, W.S. Varnum, D.B. Harris, F.J. Swenson and P.A. Bradley from LANL and S.W. Haan, S.M. Pollaine, A.S. Wan, J.C. Moreno and P.A. Amendt from LLNL, "Ignition target design and robustness studies for the Nation Ignition Facility, Phys. Plasmas 3 (5), p 2084 (May 1996)

8.) M.M. Marinak, B.A. Remington, S.V. Weber, R.E. Tipton, S.W. Haan, K.S. Budil, O.L. Landen, J.D. Kilkenny, and R. Wallace, 'Three-Dimensional single mode Rayleigh-Taylor experiments on Nova," Phys. Rev. Lett. 74, 3677 (1995)

9.) R.W. Moir, "The High-Yield Lithium-Injection Fusion-Energy (HY'LIFE)-H inertial fusion energy (IFE) power plant concept and implication for IFE," Physics of Plasmas 2 (6) 2447-2452 (1995)

10.) R.O. Bangerter and J.D. Lindl, "Gain calculations for radiatively-driven ion and laser targets", Lawrence Livermore. NAtional Laboratory, Livermore, Ca., UCRL-50055-86/87, pp2-160 to 2-168

11.) D.D.-M. Ho, J.D. Lindl, and M. Tabak, "Radiation converter physics and a method for obtaining the upper limit for gain in heavy ion fusion," Nucl. Fusion 34, 1081 (1994)

12.) Max Tabak, Private Communication (1996)

13.) George Allshouse, presentation to ICFAC committee, June 6-8, 1995

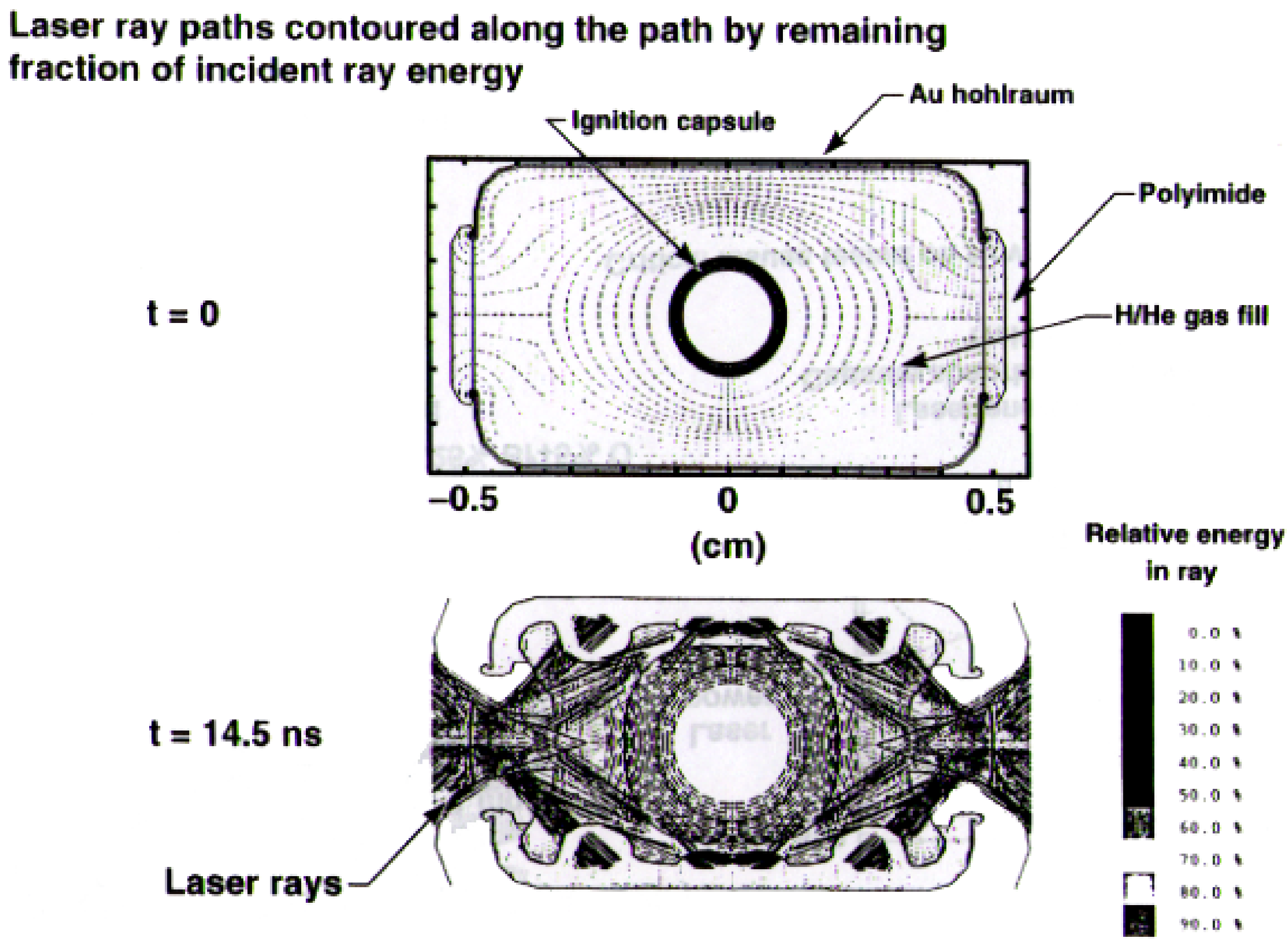
14.) Max Tabak, Private Communication (1990)

15.) J. W-K. Mark and J. D. Lindl, "Symmetry issues in a class of ion beam targets using sufficiently short direct drive pulses", AT Conference Proceedings 152, Heavy Ion Inertial Fusion, Washington, D. C. (1986), p 441

16.) C.P. Verdon, "High-performance direct-drive capsule designs for the National Ignition Facility," Bull. Am. Phys. Soc. 38, 2010 (1993)

17.) Max Tabak, James Hammer, Michael E. Glinsky, William L. Kruer, Scott C. Wilks, John Woodworth, E. Michael Campbell, and Michael D. Perry, "Ignition and high gain with ultrapowerful lasers", Phys. Plasmas p 1626, (May 1994)

18.) S.C. Wilks, W.L. Kruer, M.Tabak, and A.B. Langdon, "Absorption of Ultra-Intense Laser Pulses", Phys. Rev. Lett. 74, 1383 (1992)

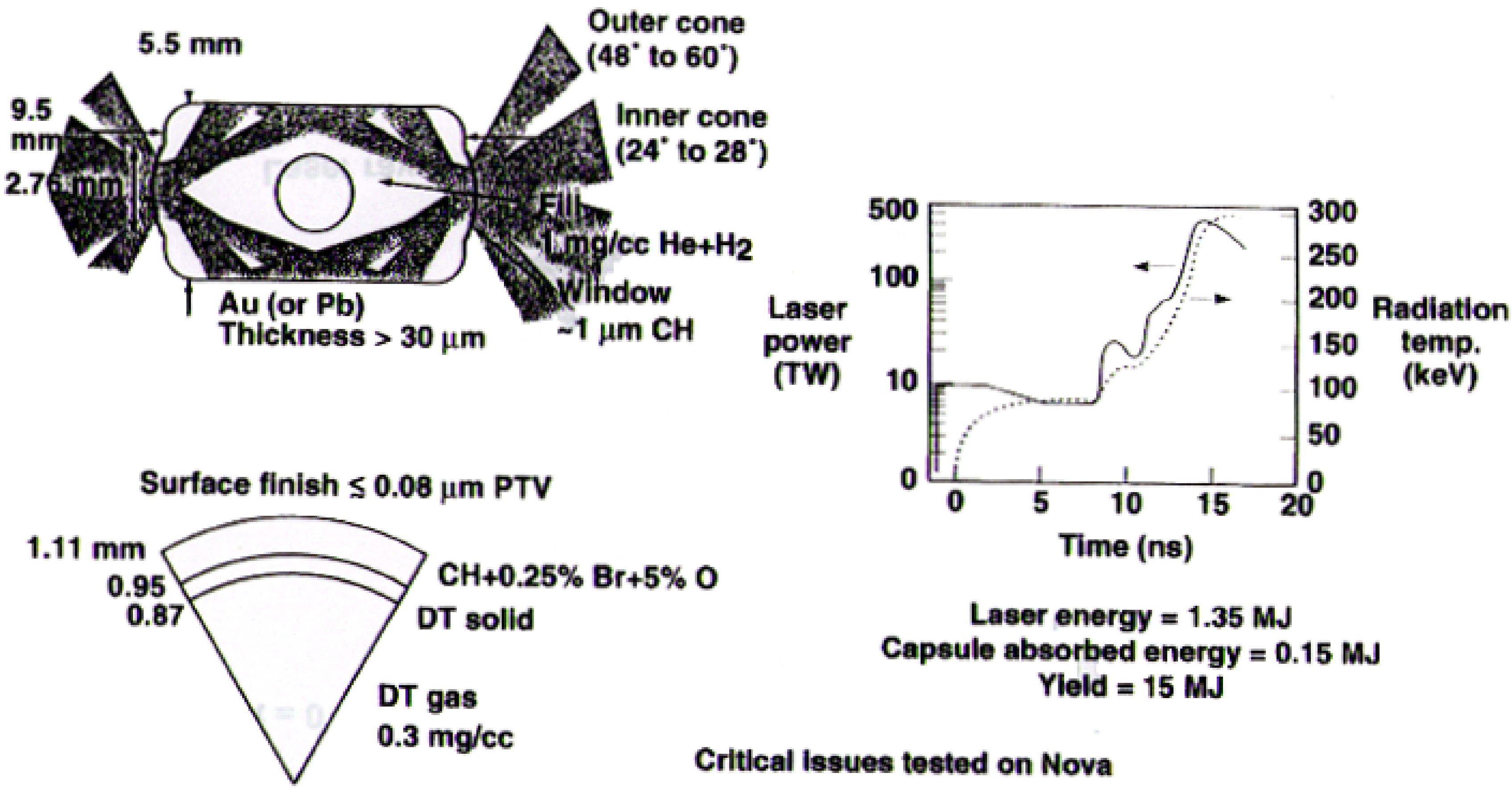


05-00-0496-0658pb02

Figure 2. We perform 2D calculations of NIF ignition targets to model accurately the coupling of the laser rays, the hohlraum, and the capsule.

Los Alamos

02/JDL/pdd



50-05-0494-1608Cpb01

Figure 1. NIF baseline targets achieve ignition in both LLNL and LANL detailed calculations which use physical models tested on Nova experiments.

30.CN/tee

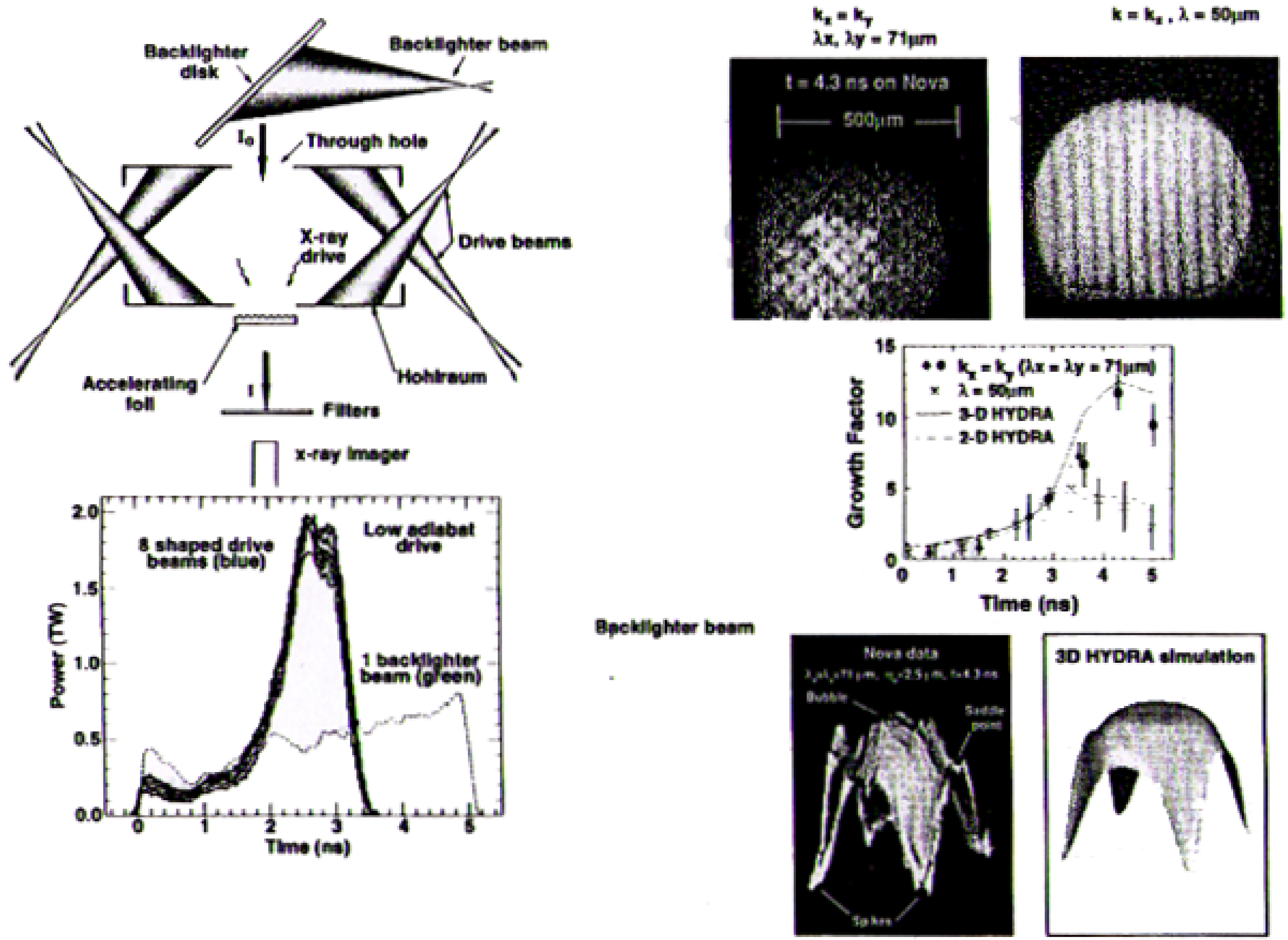
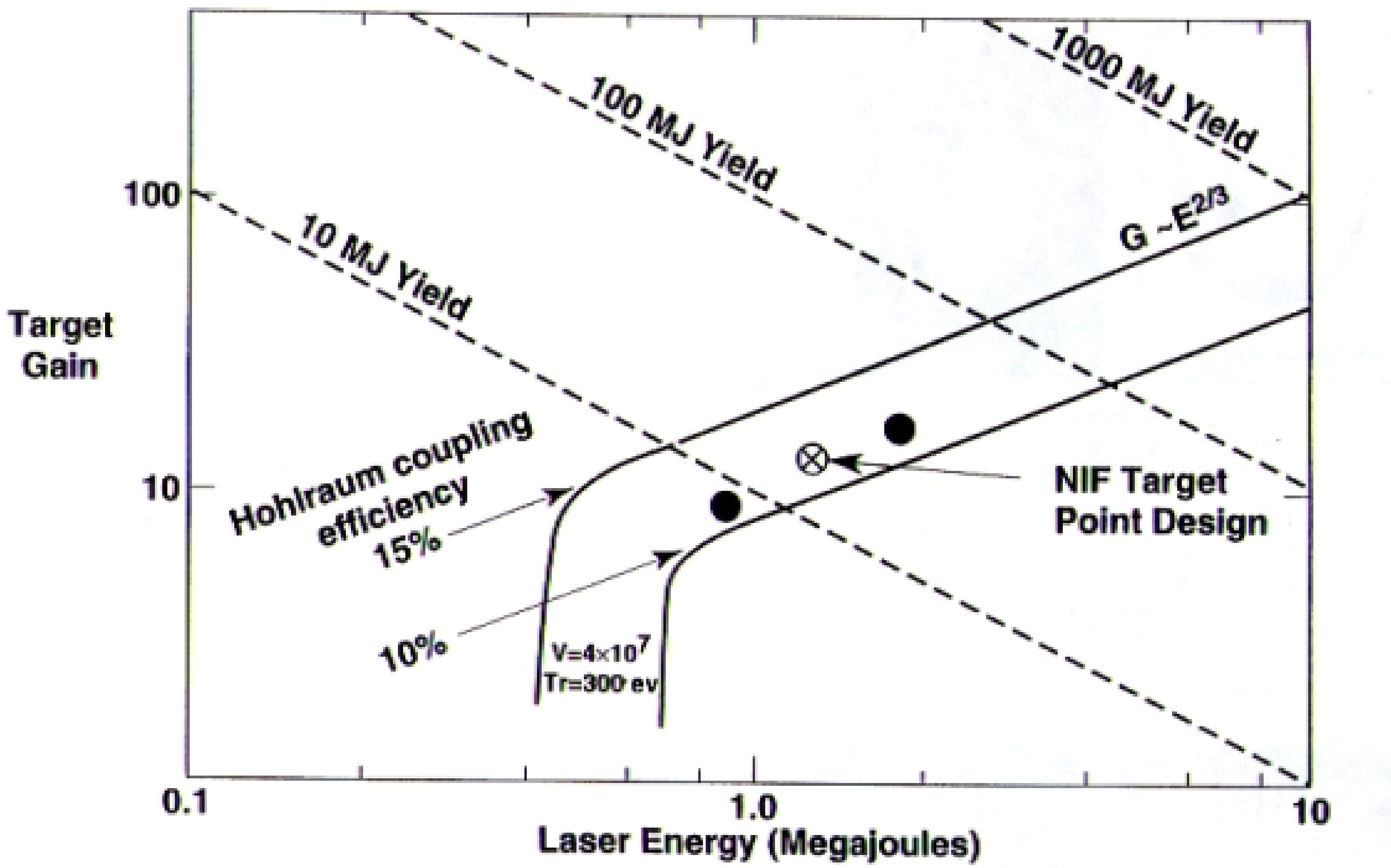


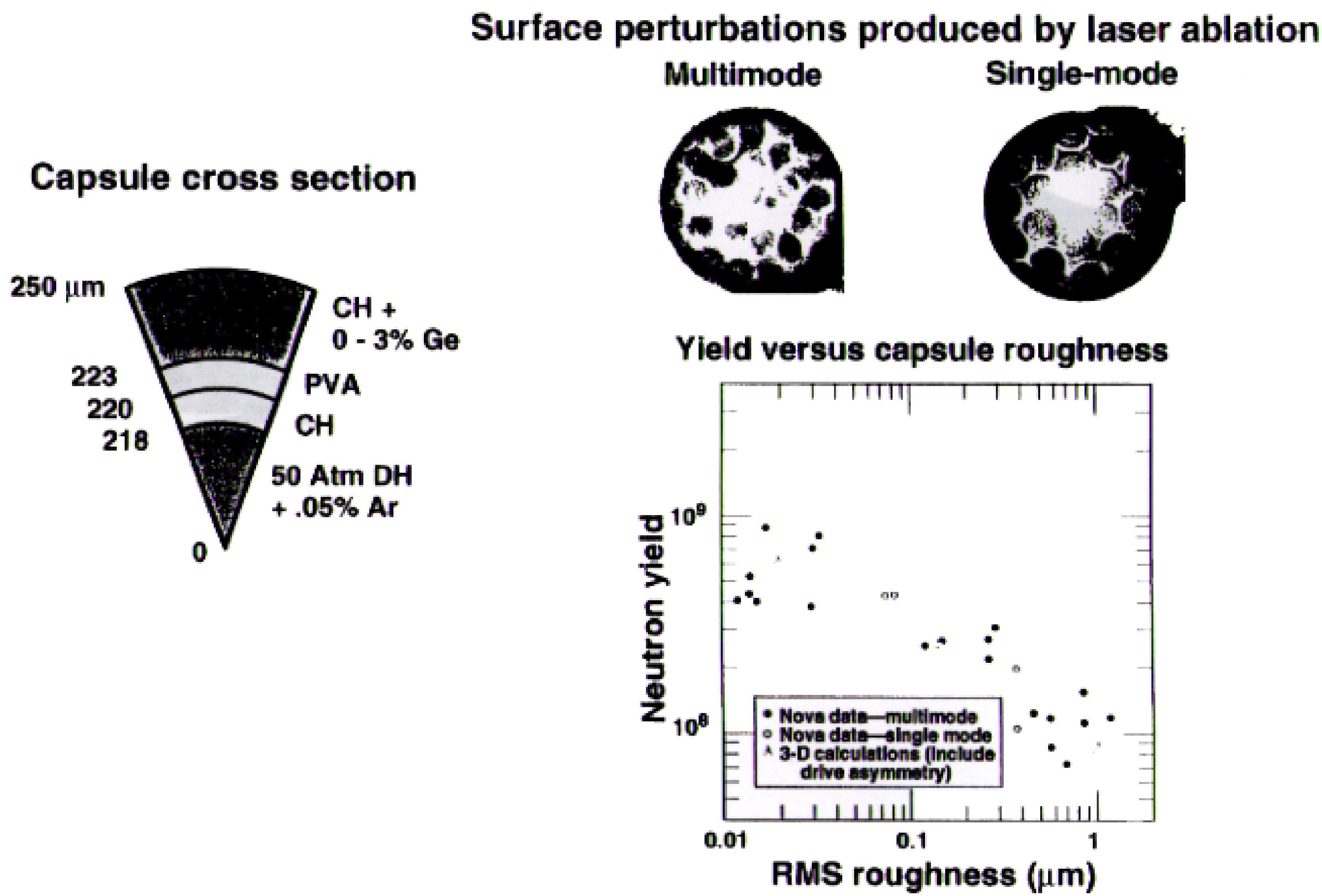
Figure 4. The measured growth of planar hydrodynamic instabilities in ICF is in quantitative agreement with numerical models.



08-00-1093-3619B

Figure 3. The National Ignition Facility (NIF) is being designed to demonstrate ICF capsule ignition and propagating burn.

13JDL/ase



96-00-0696-1446B

Figure 5. Capsules with deliberately perturbed surfaces have degraded fusion neutron yields as a result of the growth of these perturbations.

Appendix C

IFE Power Plant Issues and Needed Breadth of Research

About 50 conceptual design and system studies for IFE power reactors have been carried out over the past 25 years. Eleven of these were driven by heavy ion beams. The most recent studies, PROMETHEUS and OSIRIS were published in 1992 by two industrial and university teams. Each team developed two conceptual designs, one with heavy-ions and the other with a laser-beam driver. Table I shows some of the major parameters of several heavy-ion IFE reactor studies.

These studies make it possible to identify the key technical issues for inertial fusion energy power systems. Table 2 lists the key top-level issues. A brief discussion of these issues is given below followed by the subpanel's views on near-term research priorities.

The first issue is demonstrating high gain at moderate driver energy. Most studies require a gain in the range of 70-120 for a driver output energy (transmitted to the target) of ~ 4-7 MJ. It should be noted that reactor design studies have typically focused on high-gain, multi-megajoule incident energy target concepts that are appropriate for economic power production. However, engineering development is cost limited. It therefore is worthwhile to consider if target designs that provide moderate gain (20-50) at low driver energy (1-2 MJ) are justified. Such targets would lower the facility cost associated with IFE engineering testing and fusion power demonstration.

The second issue concerns the feasibility of the indirect drive (ID) targets for heavy-ion and laser-drivers. For heavy-ion drivers some of the issues include: a) the properties of the method used to transport and focus the HI beam to the target, b) the accuracy and reproducibility of the repetitive HI target launch system which injects the ID targets to the center of the target chamber, and c) the ability of the high-z hohlraum cavity to efficiently convert and smooth the radiation incident on the DT capsule.

The issues of imploding an ID target with laser beams include: 1) plasma closure of the entrance apertures to the hohlraum, 2) accurate target tracking and pointing of the multiple laser beams to coincide with the entrance apertures of the moving ID target, and 3) accurate and reproducible indirect drive target propagation from the pellet injector to the center of the target chamber.

The third issue is the feasibility of direct drive targets. There are strong incentives to consider direct-drive (DD) targets because of higher gains. However, the feasibility and performance characteristics of DD targets are presently uncertain.

The fourth key top-level issue relates to the cost, efficiency, reliability and lifetime of the driver. The specific issues for heavy ion drivers are vastly different from those for laser drivers. The attraction of the HI approach to IFE has always been related to the fundamental technical feasibility of building a system with the required properties to drive a pellet to ignition. The basic accelerator technology is well developed, the beam physics is tractable, and existing accelerators have exhibited 25-year life-times with 95% availabilities. The key problem for HI is cost. Key issues associated with a HI cost reduction strategy include: a) space-charge limited transport of a bunched beam, and b) high current storage rings for heavy ion beams.

The key issues for, the law driver include:

1) obtaining an adequately high overall efficiency for the laser driver

2) performance, reliability and lifetime of the final laser optics

3) reliability of various components of the laser driver.

The above four issues are concerned with the target and driver. The remaining key issues relate to providing the proper chamber environment and reactor technologies related to energy conversion, fuel (tritium) generation and adequate radiation protection in a viable, reliable, and efficient high temperature system.

The fifth issue concerns the feasibility and performance of a viable wall-protection scheme. A practical IFE system requires protection of the chamber solid first wall from rapid degradation due to the extremely high instantaneous beat and particle loads associated with the X-rays and debris from the target explosion. While researchers agree on the need to protect the chamber solid wall, there is no consensus on the best means to achieve this. The two leading schemes for wall protection are : 1) thick liquid layer, and 2) thin liquid layer. In the first scheme, a thick layer of a liquid, e.g. flibe, is formed inside the chamber solid walls to form a "pocket" surrounding the microexplosion. This scheme has the added advantage of also protecting the first wall from neutron damage. Examples of key issues associated with this scheme are: 1) the ability to form a stable and uniform thick liquid layer so as to fully cover the interior surfaces of the first wall, 2) the. feasibility of forming the liquid layer so as to allow holes for the driver beams without exposing the first wall to x-rays and debris, 3) the ability to re-establish the wall protection layer after the microexplosion, and 4) the need for this liquid to contain lithium to provide adequate breeding and the ability to clear the chamber from a multi-species liquid (e.g. the molten salt flibe).

Another scheme for wall protection relies on a thin liquid metal film wetting the first wall. This concept allows greater control over liquid feeding and uniformity of the liquid layer. It can use a single-element liquid; for example, lead, which is a neutron multiplier that can also enhance tritium breeding. Examples of issues with this scheme are: a) blast effects, b) flow around geometric perturbations, and c) protection of inverted surfaces.

The sixth IFE issue is cavity clearing at IFE pulse repetition rates. Following each pellet explosion, the cavity (chamber) fills with target debris and material evaporated or otherwise ejected from the cavity surfaces. This material must be removed from the cavity before the next target is injected. This generally requires recondensing condensable gases onto the surfaces of the first wall (or more specifically the surfaces of the wall protection layer) and by pumping non-condensable gases out through large ducts. Power reactors require a repetition rate of ~3-10 pulses per second. Evacuation requirements depend on propagation limits for both targets and driver energy. Base pressure requirements determine 1) the time to evacuate the chanber, and 2) the level of protection to the first wall (and final optics) afforded by the cavity background gas. Research is needed to better understand clearing requirements, the recondensation process, and to develop design solutions.o

The seventh issue is concerned with demonstration of tritium self sufficiency, which is an absolute requirement for an IFE system operated on the DT cycle. Fuel cycle analysis shows issues associated with: a) the magnitude of the required tritium breeding ratio (TBR), and b) the magnitude of the achievable TBR. The required TBR is most sensitive to:

- tritium fractional burnup in the target
- the tritium mean residence time in the target factory
- the number of days of tritium reserve on site
- the doubling time

Studies show the required TBR is in the range of 1.05 to 1.25 depending on the specific value of the above parameters. The achievable TBR will depend on the specific design and materials of the first wall protection scheme, structural and breeding materials and void spaces occupied by penetrations (e.g., for beams).

The eight issue is demonstration of low cost, high volume target production techniques. Target production for IFE reactors will require technologies which are presently either non existent or insufficiently developed for such application. A typical 1000 MW IFE reactor requires on the oder of 10^8 targets per year. Hence, the cost per target needs to be in the range of 0.15 to 0.3 dollars for economic viability.

The ninth issue is demonstration of adequate radiation shielding of all components. The present codes and data provide adequate predictive capability. The issue, therefore, relates more to the ability to design and develop a fully integrated system in which all components are adequately protected from radiation.

The ninth issue is demonstration of adequate radiation shielding of all components. The present codes and data provide adequate predictive capability. The issue, therefore, relates more to the ability to design and develop a fully integrated system in which all components are adequately protected from radiation.

The last issue concerns pulsed radiation damage and the thermomechanicaI response of the first wall/blanket. The severity and nature of this issue will depend, to a large extent, on the viability and specific characteristics of the wall protection scheme. If a thick liquid layer for wall protection proves feasible, then radiation damage and heat loads in the first wall/blanket will be moderate and can easily utilize technologies developed in magnetic fusion. A unique issue in this case may be the need to enhance tritium breeding. On the other hand, if the first wall protection scheme does not prove feasible, then the first wall/blanket issues such as radiation damage and thermomechanical response will become exceedingly critical.

Table 1

Major Parameters of Several Heavy Ion IFE Reactor Studies

Parameter	HIBALL-II	Cascade	HYLIFE-II	Prometheus-H	Osiris
Year Publ.	'84	'90	'91	'92	'92
First Surface	PbLi	C Granules	FLiBe	Pb	FLiBe
1st Surf. Radius, m	5	5	.05	4.5	3.5
Breeding Blanket	PbLi in porous SiC tubes	Flowing Li2O granules	FLiBe jet array	Li2O in SiC structure	FLiBe in porous C cloth
Primary Coolant	PbLi	C and LiAlO2	FLiBe	Pb & He	FLiBe
Vacuum Vesel	Ferritic steel	Al	Stainless st.	Ferritic st.	C/C compos.
Accelerator type	RF Linac	Induct. Linac	RIA	Induct. Linac	Induct. Linac
Driver Energy, MJ	5	5	5	7	5
Illumination	Cyl. sym.	2-sided	1-sided	2-sided	2-sided
Target Gain	80	75	70	103	87
Yield, MJ	400	375	350	720	430
Rep-Rate, Hz	5/chamber	5	8.2	3.5	4.6
Gross Th. Eff., %	42	55	46	43	45
Driver Eff., %	27	20	20	20	28
Net Power, MWe	946 x 4	890	1083	1000	1000

Table 2

Top-Level Issues For
Inertial Fusion Energy

1	Sufficiently High Target Gain at Economical Driver Size: a) G > 30 for indirect drive with ion beams. b) G ~ 100 for direct drive with lasers.
2	Driver cost, efficiency, reliability, and lifetime: a) Demonstration of the required performance of a Driver operated in a repetitive mode. b) Performance, reliability and lifetime of final optics.
3.	Fusion Chamber: a) Feasibility and performance of a viable wall-protection scheme. b) Cavity clearing at IFE pulse repetition rates. c) Tritium self-sufficiency in a practical IFE system. d) Adequate radiation shielding of all componenets. e) Pulsed radiation damage and thermomechanical reponse of first wall/blanket, particularly for concepts without thick liquid protection.
4.	Sufficiently low cost, high volume, target production system.

Reasons for IFE Focus on Heavy Ion Driver

Reactor studies have examined fusion energy systems with both heavy-ion and laser drivers. At this stage of inertial fusion R&D, the data base is not sufficient to conclusively select a driver that will ultimately be proven to be the most attractive for fusion energy system application.

However, there are compelling reasons why the IFE program within OFES should focus only on heavy-ion drivers. The key reasons are:

1. the constrained IFE budget permits only partial development of one driver concept

2. many of the issues of the laser-driver are being addressed by the Defense Program (DP) within DOEHI development is not supported by any program other than IFE

3. the current data base, albeit limited, indicates that heavy-ion drivers have greater potential for IFE application than laser drivers because: a) HI drivers have much higher efficiency than lasers, b) HI beams have a much higher reliability than laser systems, and c) the feasibility of the final optics for a laser system remains a major feasibility issue.

For the above reasons, it appears prudent to focus the limited IFE esources on the driver to R&D of heavy ions. However, future research results may warrant a new assessment of the driver selection. In particular, if Direct Drive Targets prove feasible, higher gains will be possible and the potential of laser drivers will vastly improve. Such results coupled with advances in laser system performance, e.g. in Diodepumped solid state and KrF lasers, will make it necessary to reevaluate the selection of the best driver for IFE applications.

Breadth of the IFE Program

The IFE Program within OFES should not be limited to only the driver. IFE effective research requires devoting a part of the resources to some of the other critical scientific and technological issues such as chamber technology because: 1) these issues are critical to the feasibility and attractiveness of IFE, 2) the research results will greatly influence future research priorities for the driver and the driver-target coupling, and 3) data is needed in order to design meaningful experiments on NIF that are of relevance to IFE.

Appendix IV

Minutes of the FESAC Meeting
Of July 16-17, 1996

FUSION ENERGY SCIENCES ADVISORY COMMITTEE

Hilton Hotel
620 Perry Parkway
Gaithersburg, MD 20877
July 16-17, 1996

MINUTES

Present:
- Robert W. Conn, Chair
- Thomas B. Cochran
- Harold K. Forsen
- Joseph G. Gavin, Jr.
- Katherine B. Gebbie
- George R. Jasny
- Michael N. Knotek
- Stephen L. Rosen
- Marshall N. Rosenbluth
- P. Floyd Thomas, Jr.
- Demetrius D. Venable

DOE Representatives:
- N. Anne Davies
- James Decker
- Milton D. Johnson

Ex-Officio
- Terrence A. Davies

Introduction

In the interests of brevity, remarks made during the various presentations both by the speakers and by members of the Committee have been included in each section without reference to source.

Tuesday, July 16, 1996

Welcome/Remarks - Robert W. Conn (University of California, San Diego), Chair, FESAC

The Chairman welcomed the committee members to the meeting. He reviewed the agenda, which is attached as Appendix I, and pointed out that Dr. Martha Krebs would meet with the Committee during the afternoon of the second day of the meeting to receive the reports of the Committee. Dean Conn reminded the Committee that they had been provided with three charges, relating to a review of the major U.S. fusion facilities, of alternative concepts, and of the Inertial Fusion Program, respectively. He pointed out to members that this would be the last meeting of the Committee with the current membership. New members and a new chairman have been nominated by the Secretary of Energy. Their term of office begins on August 18, 1996. The members of the new committee had been invited to attend this meeting, and eleven of them were present.

Dean Conn emphasized the point that every review that had been undertaken regarding the fusion program, whether it be of part of the program or of the entire program, always resulted in an excellent report and suggestions that more funding be made available. In accepting reports and recommendations relating to portions of the program, it was therefore necessary for the Committee to consider and maintain a balance within the overall program.

The Chairman stated that after hearing the presentations of Dr. Jim Decker and Dr. Anne Davies, it would be appropriate for the Committee to draft its reaction to the budget process and to forward its thoughts and recommendations to the Secretary of Energy.

DOE/ER Perspective - James Decker (DOE-OER)

Dr. Decker welcomed the new members to FESAC, indicating that their duties as committee members would start, officially, in August. He expressed his thanks to Mike Knotek and Jim Callen for their work with restructuring of the fusion program. He noted that the language in the FY 1997 Appropriations Bill in the Senate had described the new restructured program as well planned, as a result of which their budget mark had been made as high as possible within their budget constraints.

Dr. Decker pointed out that DOE, with the help of the Committee, had substantially complied with the request of Congress to restructure the program. He reviewed the House and Senate FY 1997 budget marks, pointing out the very restrictive language that accompanied the House mark. Dr. Decker stated that due to a lack of champions in Congress, non-defense discretionary funding had been squeezed this year, although science-related programs had done quite well. Energy supply, on the other hand, was not perceived as a problem at the moment. He emphasized that OFES needed relief from the very restrictive language that accompanied the House mark for the fusion program.

Implementation of FEAC Restructuring Recommendations and FY97 Budget Situation - N. Anne Davies (DOE-OFES)

Dr. Davies explained the DOE responses to the restructuring recommendations made by FEAC. DOE had accepted the recommendations, which had formed the basis of the FY97 funding request, and had produced a strategic plan to implement the program. Whereas the previous program had relied upon modest advances in science and major developments in technology, the new program emphasizes advances in science. in support, Dr. Davies compared the FY96 budget with the FY97 request.

Dr. Davies explained the new Plasma Science Initiative, which was a program for university participation only. OFES had set aside \$4 million for this program, although there was a possibility that NSF might supplement it for basic plasma research. This funding would form the backbone of the Young Investigators Program and of the Opportunities in Basic Plasma Research Program. Dr. Davies emphasized that the focus of the new program was on innovation and science. She outlined the future plans for facilities, for alternative concepts, for theory and modeling, and for materials.

In referring to the change in advisory committee membership, Dr. Davies pointed out that the Committee was being enlarged and that the new membership will reflect the change in program emphasis. She explained the new organizational structure at OFES, stating that it is still emerging.

Dr. Davies analyzed the House mark as specified by the accompanying language. \$209 million was ear-marked for specific programs, leaving just \$16 million to cover \$55.2 million of other programs that had been contained in the President's request. While the Senate language was much more flexible, either mark would result in a slowing of the restructuring process plus the loss of an additional 200 persons from the program.

Discussion of Options for Dealing with the FY97 Budget Marks - FESAC

Following a discussion of the shortcomings of the prescriptive language that had accompanied the House mark, Dean Conn stated that it would be appropriate for the Committee to write to the Secretary of Energy forwarding their views. He said that a draft letter had been prepared for the Committee's review which requested that the Secretary do two things: Seek to increase the overall funding level; seek removal of the prescriptive language. Dr. Conn added that he would like the Committee's letter to be brief and to the point, indicating that fusion community leaders were writing additional letters to the Secretary, some of which would be detailed and thus would supplement FESAC's. Several suggestions for modification of the letter were made and discussed. It was suggested that the level of overseas competition should be called out in the letter since it was felt that the Committee should let Congress know that the U.S. had relinquished the lead in fusion. This recommendation was not acted upon. After modification of the draft letter, a "straw" vote was taken, which was unanimously in favor of the modified wording. A request was made, and accepted, that a further review of the "final" letter be undertaken after re-typing before a formal vote was taken and recorded.

Office of Science and Technology Policy Perspective - Ernest Moniz (OSTP)

Mr. Moniz reviewed the budget marks and emphasized the commitment of OSTP to the fusion program. He said that it was important that the credibility of FEAC/FESAC be maintained, and that the Committee must have the support of the fusion community.

Mr. Moniz provided a comparison of Administration and Congressional out-year assumptions, indicating that the future outlook was dependent upon the accuracy of many assumptions and upon the desire to balance the budget by 2001. Irrespective of whether the Administration or the Congressional path is pursued, things will still be difficult.

Referring to ITER, Mr. Moniz stated that he would like to see the EDA through to completion but that he had difficulty in seeing how the U.S. could be a full partner in construction. He emphasized that there were a large number of good programs competing with fusion for a shrinking pool of dollars. Future fusion funding will depend upon the perceived value of the program. The differences in allocations between the House and Senate adds to conferencing difficulties. Mr. Moniz acknowledged that lower fusion budgets would erode the U.S. competitive position internationally, and that continuing reductions in funding would mean that the U.S. could not be an international player at all, and could lead to erosion of the current community unity.

Continuing Discussion of the Letter to the Secretary of Energy - FESAC

Upon resumption of discussions, the Committee reviewed the final version of the letter to the Secretary of Energy. The motion was made and seconded that the letter be sent to the Secretary as written. The motion was passed by unanimous vote.

Highlights of FESAC Report on the Major Facilities Charge - James D. Callen (University of Wisconsin), Hutch Neilson (ORNL)

Drs. Callen and Neilson reviewed the findings and recommendations of the panel that had undertaken the facilities study, explaining the scientific issues, their relative importance, and how each facility will contribute to their understanding. They thanked all who had taken part in the review for their help. The panel's report had been forwarded to Dr. Conn who, in turn, had forwarded it to DOE with the Committee's letter of transmittal.

In answer to questions, the presenters indicated that the issue of participation by industry, other than by General Atomics, had not been taken up specifically during the facilities review. Neither was the review undertaken in the context of a formal assessment of worldwide facilities, although two of the panel members had been selected from overseas programs to ensure that the panel as a whole clearly understood the capabilities of overseas facilities. The panel had not reviewed what should happen to the facilities under other budget scenarios: This had not been within the scope of the charge. Very difficult decisions would have to be made at lower budget levels and these should be tackled by the new FESAC, not by the panel, but with advice and input from Scicom if requested. All facets of the program that had been suggested by the panel were important to ITER and could potentially provide the U.S. with ITER credit.

Scicom Report to FESAC on the Alternatives Charge - James D. Callen (University of Wisconsin), Farrokh Najmabadi (University of California, San Diego)

Dr. Conn discussed the charge stating that the review was directed at recommending an investment strategy for funding alternative concepts, in particular taking cognizance of the international fusion program. The objective was to produce an overall strategy for a U.S. alternatives concept development program that would include experiment, theory, modeling and system studies, to recommend how best to collaborate internationally, to encourage new innovations, to assess scientific progress, and to determine the criteria to be used in determining when a concept was ready to move on to proof-of-principle. Dr. Conn reminded the Committee that the panel had delivered an interim report dealing with the spherical tokamak to FESAC in May.

Dr. Callen described the make-up of the panel, which had been chaired by Dr. Najmabadi, and had included consultants from the fusion programs of Japan, the United Kingdom and Germany.

Dr. Najmabadi described the panel's activities and provided the background to the review. The term alternative concept had been taken as referring to magnetic configurations other than the standard or advanced tokamaks. The panel had found that a programmatic as well as a cultural distinction existed between mainline and alternative research. Alternatives and tokamaks are viewed by OFES and by part of the fusion community as competitors rather than as being complementary, thus ignoring the strong connection that exists between most magnetic confinement approaches. Dr. Najmabadi outlined the concepts research plan that had been suggested by the panel, together with a strategy for its implementation, described the anticipated benefits, and defined the various stages of development that a new concept was likely to go through. While it was agreed that peer reviews should be a part of the process, the danger exists that these could squeeze out highly innovative concepts. The establishment of a Concept Development Panel was recommended, with this role possibly being played by Scicom. Typical review and selection processes, applicable respectively to the concept exploration and proof-of-principle stages, were presented.

The status of spherical tokamaks was reviewed and the suggestion made that this concept is ready to move to the proof-of-principle stage. The status of stellarators and that of other magnetic confinement techniques were discussed. A series of interim recommendations, pending the establishment of a Concept Development Panel, was presented.

Scicom's Future Role - James D. Callen (University of Wisconsin)

Dr. Callen took the opportunity to ask if Scicom was still needed, now that a larger, more fusion-oriented FESAC was being formed. He pointed out that the community, including many panelists, were unhappy with the trend towards the establishment of many, smaller panels, and would prefer that one, larger body, review everything. He suggested that this matter should be dealt with by the new committee and new chairman.

Discussions on Alternatives Report - FESAC

The Committee discussed the report of the panel and reviewed Dr. Callen's letter to Dean Conn on the report. Dr. Conn pointed out that the letter contained six major points and recommendations. Again, each individual topic had been pronounced good and in need of increased funding, but the funding simply was not available. He suggested that the Committee should strive to achieve a balance. After further discussion of the letter, it was agreed that it should be modified overnight and reviewed again in the morning.

Wednesday, July 17, 1996

Report to FESAC on the Inertial Fusion Energy Charge - John Sheffield (ORNL), John D. Lindl (LLNL), Mohamed A. Abdou (University of California, Los Angeles)

Dr. Sheffield reviewed the charge, presented the make-up of the panel, and outlined it's meeting agendas. He described the basic principle behind the technology that was under review, illustrated a basic system, and detailed the technical issues involved. The major uncertainties needing resolution include the driver, beam focusing, pellet manufacture, pellet positioning, and clearing of the chamber after a fusion reaction.

Dr. Sheffield described the changes and progress that had occurred since the heavy-ion driver program had last been reviewed, during the seventh meeting of the initial FEAC. He outlined the challenges, the future needs, the structure of an integrated research experiment, and the criticality of the time-frame. Target physics issues were presented, together with a list of future priorities. Budget implications were analyzed.

Dr. Sheffield contrasted Defense Program applications with energy applications. Defense applications require that a single pulse of energy only hit the target, and are such that ample time can be left for the chamber to clear before firing the next pulse. On the other hand, energy production requires a continuous procession of pulses, typically at 4 Hz, and the chamber needs to be cleared in-between each pulse. He expressed concern that in the present budget circumstances the panel had recommended increasing the funding for this program, and speculated that Defense Programs might wish to help by contributing to it.

The Committee discussed the chamber exhaust problem, and raised concern over the very large diameter needed for the heavy ion accelerator ring.

Dr. John Lindl pointed out the synergism between laser target designs and heavy-ion target designs. He described and contrasted current drive technologies, and compared their coupling to the targets. He emphasized the value of modeling in this work, describing targets in more detail and outlining what still needs to be achieved. Dr. Lindl explained the importance of energy gain and how it affected the economics of the process. Greater gain was needed for laser energy production than for heavy-ion driver energy production, since the efficiency of the laser beam production process was significantly lower than that for heavy-ion beam production. He stated that all the critical target issues were being addressed. 10^{10} energy pulses will be required from the driver over the life-time of a commercial power plant. Heavy-ion drivers have demonstrated the required longevity, reliability and desired repetition rate, as well as exhibiting better initial efficiency.

Dr. Lindl expressed uncertainty over the level of funding that might be available for this program in the out-years. The presently envisaged funding projection calls for a substantial increase in funding in FY99. That budget will be in preparation in a year's time and since it appears unlikely that the political climate will have changed by then, funding of the increase will be extremely difficult.

In answer to questions, Dr. Lindl pointed out that the size of laser needed for energy production will depend upon the eventually-realized target gain. It is possible that direct drive on the target would improve overall laser system efficiency. An on-going watch will be kept on laser experiments, and especially results from the National Ignition Facility (NIF), where both direct drive and indirect drive experiments will be performed.

Dr. Abdou described the general characteristics of IFE power plants and summarized the many conceptual design studies that had been carried out to date over a 25 year span. He outlined the potential for IFE, and enumerated the top-level issues that need resolution. These include target gain versus driver energy, the efficiency, reliability and cost of the driver, fusion chamber robustness, and the development of an economical target production system. He indicated that determining the economics of a power plant operating at 1,000 MW was not relevant, since over the time-scale of the envisaged development, production units of 2,000 MW were more likely to be needed. The IFE process will exhibit a large gain in economy as the output increases.

Dr. Abdou pointed out that next to ignition, chamber wall protection is likely to be the next most important issue. High instantaneous loads of X-rays, target debris and neutrons can lead to serious ablation of surfaces surrounding the micro-explosion. Dr. Abdou indicated that liquid wall protection schemes were being considered. He described one such system with the aid of diagrams: It utilized thick liquid, and would permit shallow land burial of the chamber and supporting structure even after 30 years of operation. A thin-liquid system is also being explored. Chamber clearing issues are important, as are target injection challenges.

A discussion of the explosive force associated with the pellets indicated that it was the X-ray portion of the yield that was most damaging. Hence the need for wall protection by a liquid that must be kept at high temperature. The choice of material for the hohlraum also presents an important issue for resolution.

During the ensuing discussion, the incompatibility of producing large amounts of energy in a system that employed extensive miniaturization was pointed out. The issue of show-stoppers was raised, but it was agreed that these, and the budgets needed to resolve them, had been adequately dealt with during the presentation.

Finalize FESAC Letter Reports on the Alternatives Charge and on the Inertial Fusion Energy Charge - FESAC

The Committee reviewed and refined the letters of transmittal that would accompany the panel reports on alternative concepts and inertial fusion energy. The motion to accept the final version of the IFE letter was made, seconded, and passed by unanimous vote. The final version of the alternative concepts letter was also agreed to unanimously.

Executive Summary for Dr. Martha Krebs and Dr. James Decker - FESAC

Dr. Krebs thanked the Committee for its work in assisting the Department with restructuring the fusion program, indicating that special thanks were due to two persons. She then presented Mike Knotek with a plaque containing the Distinguished Associate Award, which had been signed by the Secretary of Energy. Finally, she gave a special vote of thanks to Bob Conn, not just for his chairmanship of the restructuring process, but for the five years that he had served as Chairman of the Committee.

In referring to the appropriations marks, Dr. Conn informed Dr. Krebs that FESAC had developed a response that was directed to the Secretary. In essence, the response urged two actions: That the Secretary seek improved funding; that the Secretary request removal of restrictive language.

Dr. Conn then reviewed the IFE transmittal letter, and followed this with a review of the alternative concepts letter of transmittal. He stated that the response to the spherical tokamak charge had been forwarded previously and had not been dealt with specifically at this meeting. However, it had been integrated into the final transmittal letter. Dr. Conn emphasized that distinctions between mainline and alternative concepts could become poisonous, that it was highly desirable to promote the change in culture that had been recommended in the panel's report, and that the Committee had agreed with the notion of a Concept Development Panel.

With respect to the IFE program, Dr. Conn pointed out that one recommendation had been to appoint a joint Defense Programs/Energy Research steering committee, to coordinate those declassified activities that were common to both programs. This might be difficult since Defense Programs had just dissolved its ICF advisory committee. Nevertheless, optimization of both programs needs to be assured, and overlap and redundancy between them eliminated.

Terrence A. Davies
School of Engineering
University of California, San Diego
July 22, 1996

Appendix I

FUSION ENERGY SCIENCES ADVISORY COMMITTEE MEETING
July 16-17, 1996

Hilton Hotel
620 Perry Parkway
Gaithersburg, MD 20877
July 16-17, 1996

A G E N D A

Tuesday, July 16, 1996

9:00 AM	Welcome/Opening Remarks	Conn
9:15 AM	DOE/ER Perspective	Decker
9:45 AM	Implementation of FEAC Restructuring Recommendations	Davies
10:15 AM	Discussion of Options for Dealing with the FY97 Budget Marks	FESAC
11:00 AM	Office of Science and Technology Policy Perspective	Moniz
11:30 AM	Continue Discussion of the Letter to the Secretary of Energy	FESAC
12:30 PM	Lunch	
2:00 PM	Highlights of FESAC Report on the Major Facilities Charge	Callen/ Neilson
2:30 PM	Scicom Report to FESAC on the Alternatives Charge	Callen/ Najmabadi
	Scicom's Future Role	Callen
4:00 PM	Discussions on the Alternatives Report	FESAC
5:30 PM	Adjourn	

Wednesday, July 17, 1996

9:00 AM	Report to FESAC on the Inertial Fusion Energy Charge	Sheffield/ Lindl/Abdou
11:00 AM	Finalize FESAC Letter Reports on the Alternatives Charge and on the Inertial Fusion Energy Charge	FESAC
12:00 Noon	Lunch	
1:30 PM	Continue Work on Letters	FESAC
3:30 PM	Executive Summary for Dr. Martha Krebs and Dr. James Decker	Conn/ FESAC
5:30 PM	Adjourn	